THE UNIVERSITY OF MICHIGAN
JUL 5 1960
ENGINEERING LIBRARY

Journal of the Institute of Petroleum

VOL. 46 MAY 1960 No. 437

CONTENTS

Symposium on Flow Properties of Admiralty Fuel Oils

128 **The Practical Conditions of the Storage of Admiralty Fuel Oils**
By D. Wyllie and W. E. L. Taylor

143 **The Full-Scale Pumping of Admiralty Fuel Oil and its Relation to Laboratory Tests**
By T. C. Davenport and R. J. Russell

161 **The Study of Fuel Oil Pumpability using a Laboratory Pumping Rig**
By D. Wyllie and J. T. Jones

Abstracts 664–848

Book Reviews

Additions to the Library

PRICE 10s 0D A COPY OR £4-14-6 YEARLY *POST FREE*

Published by the Institute of Petroleum 61 New Cavendish Street London W1

Printed in Great Britain by Richard Clay and Company Ltd Bungay Suffolk

COUNCIL, 1959–60

President

C. M. Vignoles, C.B.E., M.A.

Immediate Past-President

The Rt. Hon. Lord Geddes, C.B.E., D.L., M.A.

Vice-Presidents

C. Chilvers, B.Sc., F.R.I.C. H. Hyams T. W. Mathias, O.B.E., M.A.

Members of Council

J. G. Annan, B.Sc.
V. Biske, B.Sc., LL.M., F.R.I.C.
G. A. Dickins, B.Sc.(Hons), F.R.I.C., M.Am.Chem.Soc.
E. J. Dunstan, M.Sc., M.I.Chem.E.
A. J. Foster
F. L. Garton, M.A., B.Sc.
Sir Stephen Gibson, C.B.E., M.A., M.I.Mech.E.
R. H. W. Hamilton, M.A.
L. L. Hosking, B.E., M.I.C.E., A.M.N.Z.I.E.
M. E. Hubbard, B.A., M.I.Mech.E.
C. S. Newey, B.Sc.
K. E. W. Ridler, Ph.D.
D. L. Samuel, B.Sc., A.R.I.C.

Representing the Branches Committee

C. W. Banyard, B.Sc.(Eng.) J. H. M. Clark, T.D., A.C.A.
D. H. Tullis, B.Sc., A.R.T.C., A.R.I.C., M.I.Chem.E.

Honorary Treasurer

O. F. Thompson, O.B.E.

Honorary Secretary

W. M. Catchpole, M.A.

Honorary Editor

E. B. Evans, M.Sc., Ph.D., F.R.I.C.

Honorary Associate Editor

D. L. Samuel, B.Sc., A.R.I.C.

General Secretary

D. A. Hough, T.D., F.I.A.C.

Editor

George Sell

Honorary Secretaries of Branches

Bahrain Branch: D. G. Johnstone, c/o Bahrain Petroleum Co. Ltd., Awali, Bahrain, Persian Gulf.

Essex Branch: D. Rawlinson, F.R.I.C., c/o Shell Refining Co. Ltd., Shell Haven, Essex.

Fawley Branch: C. W. Banyard, B.Sc.(Eng.), c/o Esso Petroleum Co. Ltd., Fawley, Southampton.

Kuwait Branch: G. A. Lee, c/o Kuwait Oil Co. Ltd., Ahmadi, Kuwait.

London Branch: J. H. M. Clark, T.D., A.C.A., c/o Mobil Oil Co. Ltd., Caxton House East, Westminster, S.W.1.

Northern Branch: H. Kaye, B.Sc., A.M.I.Chem.E., c/o Manchester Oil Refinery Ltd., Twining Road, Trafford Park, Manchester 17.

Scottish Branch: W. M. Stirling, A.H-W.C., A.M.I.E.E., Scottish Oils Ltd., Middleton Hall, Uphall, Broxburn, W. Lothian.

South-Eastern Branch: D. K. L. Morgan, B.Sc., c/o BP Refinery (Kent) Ltd., Isle of Grain, Rochester, Kent.

South Wales Branch: G. L. Jenkins, BP Refinery (Llandarcy) Ltd., Llandarcy, Glam.

Stanlow Branch: A. S. Brooman, B.Sc., 11 Grange Crescent, Hooton, Wirral, Cheshire.

Trinidad Branch: W. G. Poole, B.Sc., A.R.S.M., F.G.S., c/o Texaco Trinidad Inc., Forest Reserve, Fyzabad, Trinidad, B.W.I.

Yorkshire Branch: A. Furness, c/o J. W. Miller and Son Ltd., Hillside Oil Works, Brighouse, Yorks.

SYMPOSIUM ON FLOW PROPERTIES OF ADMIRALTY FUEL OILS

A MEETING of the Institute of Petroleum was held at 61 New Cavendish Street, London, W.1 on 6 January 1960, the chair being taken by the President, C. M. Vignoles, C.B.E.

After he had formally opened the meeting, the President said that he proposed to hand over the chairmanship to Dr C. M. Cawley, the Chief Scientist to the Ministry of Power and, more appropriately in connexion with the subject to be discussed, chairman of the Admiralty Fuels and Lubricants Advisory Committee.

FIRST SESSION

Dr C. M. Cawley, C.B.E.: It gives me a very great deal of pleasure to be called upon to take the chair this afternoon at this symposium on the flow properties of Admiralty fuel oils. This arises from the work of AFLAC, the Admiralty Fuels and Lubricants Advisory Committee, and I would like to say a few words about this committee before we get down to our business proper. I believe that it provides a most instructive example of an alliance of many interests to achieve a practical objective. It was set up in 1950, so it is perhaps appropriate after a decade of co-operation that we should be talking about it now.

It was called the Admiralty Oil Quality Committee in the beginning, but it was essentially the same committee. As I see it, the point of particular interest is that its work has involved a major co-operative effort between the Admiralty, the universities, other Government Departments, and the petroleum industry. The great contributions of many interests and many people have led to most fruitful co-operation and I may say that the Admiralty have been extremely pleased with the results.

It is of interest to ask why the work has, as I believe, been so successful. I think it is partly because all the people concerned in it have been united by a common interest in the problems they have been investigating, from the scientific, technical, technological, economic, and strategic points of view. But a most important factor was that, at the very outset, the Committee was guided by people of energy and enthusiasm, who were impressed by the importance of their task. It is invidious to mention names, but I would just like to refer to three people who had a very great part to play in this: they were Lord Geddes, Professor F. H. Garner, and Captain L. E. S. H. Le Bailly. They were supported by many other people, both inside and outside the organization, but we owe a very great deal to their enthusiasm, vigour, and dedication to the work in hand.

Another most important factor, which has impressed me throughout the work of the committee, over these years, has been the tremendous effort which the petroleum industry has put into the job. The Admiralty are greatly appreciative of this, as they are also of the work of the universities and other Government Departments, particularly the DSIR.

I have been speaking of the work of the committee. We are not here this afternoon to discuss the whole of that, but only one part of it. Under the main committee, there are two sub-committees, a Fuels Sub-Committee, under the chairmanship of Professor Frank Morton, and a Lubricants Sub-Committee, under the chairmanship of Professor E. S. Sellers. Both sub-committees work through a number of panels, each specializing in a particular subject. We are here to discuss the work of Panel F, of which Professor Sellers has been the chairman for the past three or four years, and which is a panel of the Fuels Sub-Committee. The panel is investigating the flow properties and the pumpability of residual fuel oils, a problem with which the Admiralty and the Royal Navy have been much concerned over many years.

I must mention the three elements of this problem. First, the viscosity of the fuels in Admiralty storage has at times increased to such an extent as to render the fuel unpumpable; secondly, cases have occurred, and could occur again without an adequate specification safeguard, in which the viscosity of fuels in HM ships' tanks has increased when the ships were laid up, to such an extent as to render the fuels unpumpable; and thirdly, under action damage conditions in the Arctic, or Arctic waters, existing fuels could become unpumpable. These, then, were the basic facts which caused concern in the Navy and led to the setting up of the Panel to study the factors affecting pumpability.

The two main tasks before the Panel were: (1) to find ways and means of assessing the pumpability of a fuel in a given condition, and (2) to predict that pumpability after a long period of storage.

I cannot attempt to mention the names of all the many people who have served on the Panel, but I must pay a tribute to the Chairmen, Professor F. H. Garner, Dr A. C. Monkhouse, and Professor E. S. Sellers. The members of the Panel have come from the petroleum companies, Birmingham University, and the Fuel Research Station of DSIR.

The work, as I have said, has been carried out as a major co-operative effort, groups being formed to make studies of particular aspects of the problem, in the field and in the laboratory, practical and fundamental, throughout the whole period.

In presenting the results to the symposium to-day, various aspects of the work have been written up by Panel members. Although the papers are the work of individuals, and almost certainly contain some of their personal views, nevertheless they represent the work of the Panel and of the various participating organizations as a whole. The arrangement made by Professor Sellers and the Panel was that the authors would endeavour to give a picture of the entire study, and not merely to write up a piece of work which they themselves had carried out.

These, then, are the papers that we are to hear, and I first ask Professor Sellers to give us a brief technical introduction to the work.

M

Professor E. S. Sellers: It is appropriate that we should begin by examining what is required in the present Admiralty specifications for fuel oils and comparing therewith the usual commercial specifications.

The important features of Specifications E-in-C 0–1 and E-in-C 0–1A for Schedule 390 and 390A fuels are given in the paper "The Practical Conditions of the Storage of Admiralty Fuel Oils." This will be the first paper to be discussed, and Paragraph 2, Types of Fuel, shows that the present specification attempts to provide a safeguard with regard to pumpability under adverse conditions, so that the specification does rely on the basic idea that pumpability can be controlled by a combination of flow point and Redwood No. I viscosity at 122° F. These are given in detail under sub-paragraphs (*a*) and (*b*). In comparison I would direct attention to the British Standards specification. In BS 2869 : 1957, the respective viscosities at 122° F of the E, F, G, H classes of oil are 148 sec, 510 sec, 1500 sec, and 2800 sec. In general, the furnace fuel oils for marine commercial use have a much higher viscosity than those for Admiralty use. Also, in the BS specification there is no pour point (or flow point) requirement. But the Admiralty and the AFLAC organization have never been satisfied that the existing specification does provide an adequate safeguard, and for a long time this Panel has been concerned with trying to find some laboratory tests which would give an adequate safeguard when oil was subjected to the environment mentioned by the chairman.

The furnace fuel oils in Admiralty use are made up by blending heavy residue with a distillate fraction, and it has been known for a long time that these oils, when they are stored for lengthy periods, develop what is usually called some "structure." The structure is literally a structure of micelles of wax, asphaltenes, or resins, in some indeterminate form, which does have a sort of interlocking effect and which does resist flow. We know that this structure can be broken down by mechanical shearing action, and that the rate at which the breakdown occurs depends upon the rate of shear, or on the shearing stress applied. This is shown clearly in Fig 4 of the paper on "The Measurement of Flow Properties by Coaxial Cylinder Viscometer." It will be seen how rapidly the viscosity decreases when the oil is sheared: at 300 dynes/cm² the viscosity is reduced quite quickly; at 400 dynes/cm² much more quickly; and at 500 dynes/cm² it comes down very rapidly indeed and fairly soon attains, but still taking about 20 minutes, what we call (fairly loosely I am afraid) an "equilibrium viscosity." But note that under a relatively low shearing force, of 200 dynes/cm² even after 3 hours and more, the oil is still not down to its final equilibrium viscosity. This, then, is the main characteristic of the oils with which we are concerned, under the conditions that offer to us the most concern. When this structure does develop, can we start a pipeline flowing, can we keep it flowing, and how fast will the oil flow?

Looking at this as a technical question now, it is quite clear that if we are going to attempt a programme of work which has as its ultimate objective the prediction of the flow properties of fuel oil after prolonged storage and after exposure to a particular environment, we have to take into account the following factors: first, the practical conditions of storage, and the change of the oil characteristics with time; second, the size and arrangement of pump suction systems, both ashore and in ships, since it is these which will determine the amount of shear which is applied; third, the actual pumping rate possible in existing installations, especially when the oil is in an initial gelled or semi-gelled condition, and the relation between these pumping rates and certain laboratory tests; fourth, laboratory experimental work, which in turn must be subdivided into: (i) a fundamental investigation into the nature of the structure in the oil and the kinetics of build-up and breakdown under determined conditions; (ii) the discovery of some method of temperature cycling procedure which will produce in the oil some structure which would have the effect of increasing the viscosity of the oil to the highest figure which could be expected after prolonged storage at surface ambient temperatures; (iii) the provision of a large-scale facility which would enable simulation of actual pumping operations to be carried out under controlled conditions of shear stress, temperature, and time; and (iv) the development of a reasonably simple laboratory test of satisfactory repeatability and reproducibility which could be used for specification purposes. That is the technical statement of what this Panel has been trying to achieve. In this symposium the first three papers will give an account of storage conditions, of how the oil properties are affected by the conditions, of large-scale trials both ashore and in ships, and of the large-scale experimental rig for pumping experiments. The later papers will be concerned with the supporting laboratory work.

The three following papers were then presented in summary:

THE PRACTICAL CONDITIONS OF THE STORAGE OF ADMIRALTY FUEL OILS *

Prepared by D. WYLLIE † (Fellow) and W. E. L. TAYLOR † and presented by D. WYLLIE

1. INTRODUCTION

THE behaviour of furnace fuel oils on pumping and the relationship between pumping rates and laboratory measurements of the viscosity under controlled shear rate or shear stress have been discussed in other papers.[1, 2] The correct forecasting of the pumping rates achievable (with any oil in store) depends on these laboratory measurements being made on reliable samples, together with a survey of the temperature and rheological condition of the different layers of oil in the tank. The temperature and condition of the oil depend in turn on the nature of the oil and on the climatic temperatures under which it has been stored. The temperatures of the oil in above-ground tanks and sampling methods for rheological measurement

* MS received 29 October 1959.

† Admiralty Oil Laboratory, Brentford, Middlesex.

of the oil have been an interesting study. The work has been mainly confined to fuels having Redwood No 1 viscosities at 122° F not exceeding 200 sec, with an occasional fuel having a viscosity up to 300 sec. The study has covered fuels from several sources.

2. TYPES OF FUEL

The furnace fuel oils under discussion are residual fuels cut back with sufficient middle distillates to bring them within the Admiralty Specification. The specification limits have varied over the past 20 years, but until the introduction of E-in-C 0-1 and 0-1A Specifications for Schedule 390 and 390-A fuels no real attempt was made to define a pumpability test. These specifications rely on the basic idea that pumpability could be controlled by a combination of flow point and Redwood No. 1 viscosity at 122° F.

The flow point test was the result of an early attempt to evolve a technique which would predict the pour point that a freshly blended oil might attain after five years storage. The basis of the test had been evolved by workers at the British Petroleum Company's Research Station,[3] and the development of the present specification test is described in the accompanying paper by Ackroyd, Hosking, and Lowe.[4]

A somewhat arbitrary selection of limits [5, 6] for flow point and Redwood viscosity were then selected for specification purposes. These were:

(*a*) With oils having flow points not exceeding 30° F the upper limit of viscosity was fixed at

TABLE I

List of Oils examined in Above-ground Tank Storage

Oil No	Flow point, ° F	Viscosity at 122° F Redwood No 1 sec	Source	Refinery	Rating on Spec. for		Used in cold pumping trials	Viscosity level indicated in figure
					390-A fuel	390 fuel		
1	0	196	Caribbean	I	Pass	Pass	Yes	7
2	0	159	Mixed Caribbean	—	Pass	Pass	No	7
3	0	186	Probably Caribbean	—	Pass	Pass	No	7
4	0	204	Continental refinery	E	Borderline	Pass	No	7
5	0	275	Mixed origin	—	Fail	Pass	No	7
6	0	278	Caribbean	J	Fail	Pass	No	7
7	0	about 275	U.K. refinery	D	Fail	Pass	Yes	7
8	9	193	Caribbean	I	Pass	Pass	No	7
9	0	189	Caribbean	I	Pass	Pass	No	7
10	0	190	Caribbean	I	Pass	Pass	No	7
11	0	191	Caribbean	I	Pass	Pass	No	7
12	10	250	Caribbean	J	Fail	Pass	Yes	7
13	15 to 20	194	Caribbean	—	Pass	Pass	No	7
14	15 to 20	194	Continental refinery	E	Pass	Pass	No	7
15	25	175	Continental refinery	E	Pass	Pass	No	7
16	25	163	Middle East: U.K. refined	A	Pass	Pass	No	7
17	25	168	Middle East: U.K. refined	A	Pass	Pass	No	7
18	25	191	U.K. refinery	C	Pass	Pass	No	7
19	30	161	Middle East: U.K. refined	A	Pass	Pass	Yes	8
20	30	158	Middle East: U.K. refined	A	Pass	Pass	No	8
21	30	163	Middle East: U.K. refined	A	Pass	Pass	No	8
22	30	180	Middle East refinery	H	Pass	Pass	No	8
23	30	196	Middle East refinery	H	Pass	Pass	No	—
24	30	165	Middle East: U.K. refined	A	Pass	Pass	Yes	8
25	30	186	U.K. refinery	C	Pass	Pass	No	8
26	35	142	Middle East: U.K. refined	B	Pass	Pass	Yes	9
27	35	205	Middle East refinery	H	Fail	Fail	Yes	9
28	35	170	Middle East: U.K. refined	A	Pass	Pass	No	9
29	35	160	Middle East: U.K. refined	A	Pass	Pass	No	9
30	40	101	U.S.A. (before 1939)	—	Pass	Pass	Yes	—
31	40	174	Middle East: U.K. refined	A	Pass	Pass	Yes	9
32	40	137	Middle East: U.K. refined	B	Pass	Pass	Yes	9
33	40	158	Middle East: U.K. refined	B	Pass	Pass	Yes	9
34	40	195	Middle East refinery	H	Fail	Fail	No	—
35	40	165	Middle East: U.K. refined	A	Pass	Pass	No	9
36	45	163	Middle East: U.K. refined	A	Fail	Fail	Yes	9
37	50	110–120	Middle East refinery	F	Fail	Fail	Yes	10
38	50	90	Middle East refinery	F	Pass	Pass	No	10
39	50	90	Middle East refinery	F	Pass	Pass	No	10
40	70	170	Middle East refinery	F	Fail	Fail	Yes	—
41	55	164	Middle East: U.K. refined	G	Fail	Fail	Yes	—
42	70	210	Middle East refinery	F	Fail	Fail	No	—

300 sec Redwood 1 at 122° F (Schedule 390 fuel). At a later date this viscosity was reduced to 200 sec Redwood 1 at 122° F (Schedule 390-A fuel). As pumping fuels at bulk temperatures below 32° F was not envisaged in the U.K., this in effect assumed that these fuels would be pumpable and that their pumping characteristics would be related largely to Redwood viscosity at 122° F.

(*b*) With fuels having flow points of 35° F or 40° F, the upper limit of viscosity was fixed at 175 sec Redwood 1 at 122° F. This envisaged some build-up of structure in the fuel as bulk temperatures fell towards 32° F, but assumed that by limiting the viscosity at 122° F to 175 sec Redwood 1 the oil would remain pumpable.

(*c*) With fuels having flow points of 45° and 50° F the viscosity of fuel was required not to exceed 100 sec Redwood 1 at 122° F. This assumed that a fuel could be pumpable below the determined flow point if the Redwood viscosity is controlled.

(*d*) No fuel having a flow point above 50° F was considered acceptable.

Very few furnace fuels supplied had viscosities below about 80 Redwood sec.

The above somewhat arbitrary limits could not forecast rates of pumping likely to be achieved with any oil. The flow point/viscosity combination did, however, afford a substantial safeguard and was in effect an arbitrary attempt to combine temperature of " gelation " with basic viscosity of the oil.

The earlier work was carried out on several different types of oil found in Admiralty storage, but whenever thickening was reported by a depot staff, a scientific team investigated the conditions. A complete list of fuels observed is given in Table I in terms of flow point, Redwood viscosity, and an indication of origin.

3. TYPES OF STORAGE

In practice, the fuel is stored unheated in large tanks until required for use or transfer. Whether the oil is then heated to facilitate movement depends on the condition of the oil and the time available for issue or transfer.

A normal storage tank has a capacity of 5700 tons, is cylindrical, 90 feet in diameter, with walls 36½ feet high. It is constructed of steel plates and has a gently sloping roof of steel plate rising from all sides to a central point. It is protected by a brick blast wall which leaves an air gap of 3–4 inches between the blast wall and the side of the tank. The sloping tank roofs are unprotected.

Fuel is supplied to or removed from the tank through a pipe passing through the side of the tank just above floor level and connected by a trunnion to two movable internal pipes called swing-arms or walking arms so as to supply or draw fuel from any desired level. The tank valve to control flow into or out of the tank is situated on the pipe where it enters the tank. It is possible to pump out a tank to within a foot of the floor level.

The only obstructions to flow inside the tank are the heating coils, which are so spaced as to offer only negligible resistance.

An important matter in relation to sampling and inspection of the oil is the means of access available. this is limited to four manholes in the tank roof and a small central cowl which is little more than an air vent. The manholes are close to the sides of the tank and equally spaced round the circumference. They permit sample pots, thermometers, or other equipment to be lowered at the tank wall and up to about 5 feet from it. Thermometers and small sampling pots can be lowered into the oil through the central vent.

A larger size of tank of 12,000 tons capacity is of the same shape but 116 feet in diameter and 45½ feet high at the wall. In these tanks there is a second ring of four manholes in the roof 23 feet from the side. In addition to the above-ground storage, considerable quantities of furnace fuel oil are stored underground.

4. DETERMINATION OF THE CONDITION OF OIL IN ABOVE-GROUND STORAGE

The methods available to the storehousemen in charge of oil tanks are extremely limited. Depot staff inspect the fuel by temperature and gravity measurement and visual observation. The temperature is determined by lowering a weighted thermometer into the oil at the various manholes and to various depths. Such measurements, although liable to error in that it may not be possible to read the thermometer sufficiently quickly after it has attained the temperature of oil at any given depth, have proved surprisingly reliable. In addition to this method samples may be withdrawn using the standard sampling pots and the temperature of the sample taken immediately. An experienced man can form an approximate estimate of the condition of the oil by observing the rate at which a weighted thermometer or a sampling pot sinks.

Scientific staff visiting depots have concentrated on measuring the temperature and viscosities of the oil with occasional attempts to estimate yield value or pour point. The simple temperature measurement technique used by depot staff was found to be reliable within about 2° F. It has, however, been supplemented in some instances by measurements using thermocouples.

Measurement of the viscosity of the oils under constant shear stress and constant rate of shear has been made on samples taken from the tank. Occasionally pour points and yield values have also been determined on the storage site and, where wax segre-

gation has been suspected, microscopic examination has also been made.

The information which has been collected is discussed under the following convenient headings.

(*a*) Temperature.
(*b*) Sampling for rheological measurement.
(*c*) Examination of samples and interpretation of results.

5. TANK TEMPERATURES

The pumping trials carried out at one depot, described by Davenport and Russell [2] gave clear proof that different oils would have different bulk temperatures in winter. In Table II the temperature of the oil issuing from the tanks into the pipeline when these oils were pumped are set out, together with flow point, Redwood viscosity at 122° F, and mean air temperatures. In each case the oil was taken from the interior of the tanks via the swing arms and not from surface layers.

In October 1953 five oils, 1, 12, 30, 37, and 40, of differing types, came into the line at temperatures close to mean air temperatures recorded for the previous month (see Table II). The trials were held on 6 to 8 October inclusive. Two oils (1, 36) pumped in October 1954 at temperatures within a few degrees of mean air temperatures for the months of September and October, which in that year differed in temperature by only 2° F (Table II).

Trials in February 1954 and February 1955 showed that only the very low flow point oils (1, 7) had cooled to prevailing mean air temperatures. In the case of the other oils the temperature of the oil pumped was at least 8° F higher and in one instance 17° F higher than the mean ambient temperatures. The temperatures were checked by samples drawn from the oil in the inner regions of the tank, except for the oil (40), which had formed so firm a gel layer at the top that sample pots could not penetrate to the warmer fluid oil beneath. The two highest flow point oils (37, 40) had the highest bulk temperatures, and both contained upper zones of gelled oil.

The other five oils, 19, 30, 31, 36, and 37, were pumped at temperatures between 43° and 49° F. Most had flow points of 40° and 45° F, which implied that the outer layers might well be sufficiently viscous at air temperatures below 40° F to retard the loss of heat from the centre of the tank. The other two, 12 and 19, had flow points of 10° and 30° F and oil temperatures of 48° and 49° F. Oil 12 was one of the very few types known to thicken considerably at temperatures well above its flow point. The other was not known to be abnormal in any way.

Shortly after the completion of these trials several consignments of oil of common origin, designated by numbers 22, 23, 27, and 34, in another depot were examined in some detail but not pumped. These had gelled to such an extent that a brick could be supported on the surface. The delivery had been made in the previous summer, but gelling had commenced on the surface at the end of October, when air temperatures were steadily falling. By the end of March, when the visit was made, mean air temperatures had commenced to rise, but the surface layer had only just started to soften. Monthly air temperatures for the district in which these tanks were situated, from the period when they were filled until the oil was eventually removed, are shown in Fig 1. Careful measurement using a weighted thermometer, with occasional verification from samples taken from the tank, showed that the temperature distribution was as shown in Fig 2. The top few inches of oil were responding to the daily temperature changes, and below this there was a zone of gelled oil several feet thick extending over the top of the tank and partially down the sides. Once this gel was penetrated, it was possible to reach fluid oil at a temperature some 10° higher than that of the outer few feet. Owing to the arrangement of the inspection manholes, it was not possible to measure tank temperatures farther than about 5 feet from the tank wall except on a centre line where the central vent could be used.

On this particular visit the sampling pots available were too large for samples to be drawn through the central vent, and temperatures on the centre line were taken by weighted thermometer only. On a larger

TABLE II

Temperature of Oil of Various Types Stored Unheated in the Same Depot

Oil No	Flow point, ° F	Redwood 1 viscosity at 122° F	Temperature of oil pumped from tank, ° F				Mean monthly air temp at time of trials, ° F	
			October 1953	February 1954	October 1954	February 1955		
1	0	196	57	37	53	36	September 1953	58·3
12	10	250	58	45	—	48	October 1953	50·3
40	70	170	60	Over 45	—	52	January 1954	37·9
37	50	110	59	49	—	51	February 1954	36·1
36	45	163	—	—	56	43	September 1954	55·8
7	Below 0	About 275	—	—	—	36	October 1954	53·8
19	30	161	—	—	—	49	January 1955	37·5
31	40	174	—	—	—	49	February 1955	35
30	40	101	58	45	—	47		

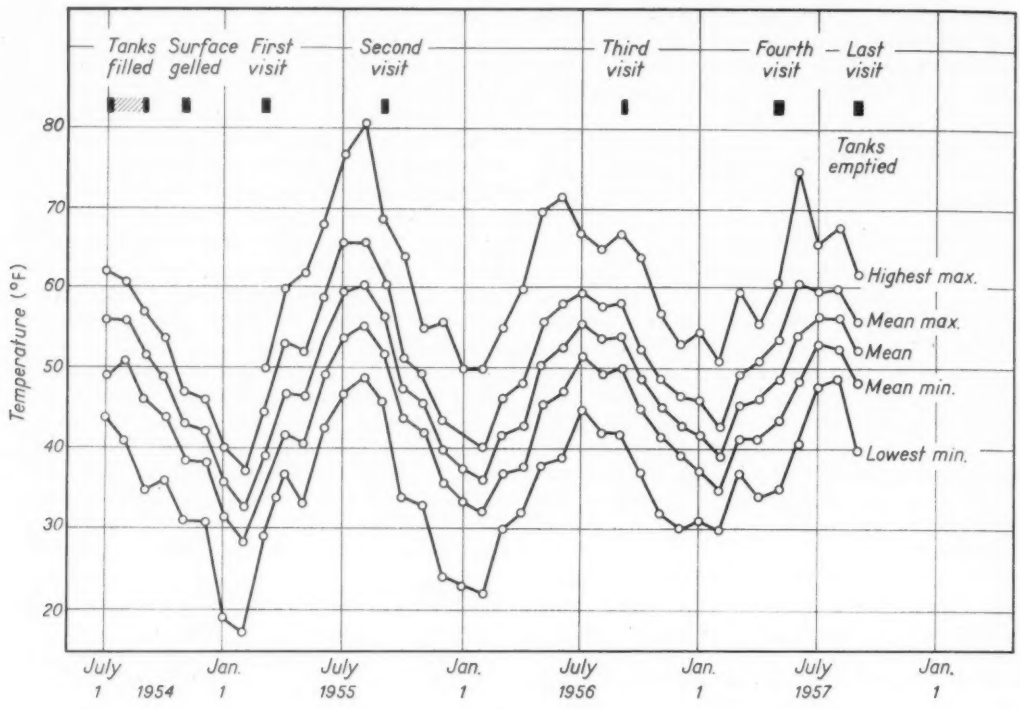

FIG 1

MONTHLY AIR TEMPERATURES NEAR STORAGE SITE OF OILS 22, 23, 27, AND 34

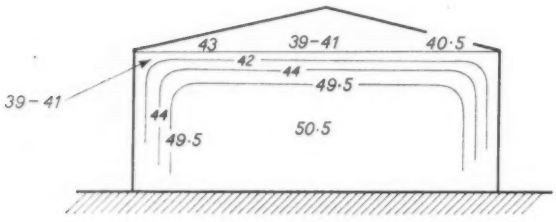

FIG 2

WINTER TEMPERATURE DISTRIBUTION, °F
(Oil 22—March 1955)

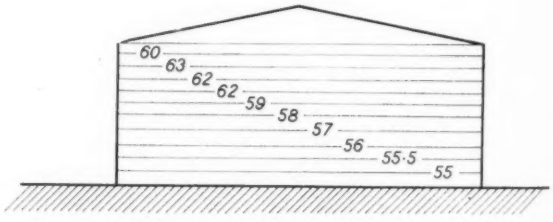

FIG 3

SUMMER TEMPERATURE DISTRIBUTION, °F
(Oil 22—September 1955)

tank, containing oil 34, temperatures were taken at the inner manholes, and they showed that temperatures 23 feet from the side and well below the surface were practically the same as those a few feet from the side. The temperatures and the extent of the gelled layer of the oil in four tanks, together with the flow point and Redwood viscosities, are set out in Table III. Pour point measurements were made by filling a pour point tube at room temperature and cooling without any pre-heating. These "as received" pour points included in Table III are in general about 10° higher than the flow points.

At the time when the oils 22, 23, 27, and 34 were reported by storehousemen as becoming thick (October 1954) and as having gelled (November 1954), mean air temperatures for ten days had been 46° and 42° F respectively. When the depot was visited the following March, "as received" pour points were 35° to 45° F, and with oil at temperatures of 39° to 47° F the outer layers of oil were still gelled. In the coldest part of the winter, when mean air temperatures fell to 33° F, there must have been a temperature differential of about 20° F between mean air temperatures and bulk oil temperatures.

At the end of that summer the oil was again inspected. All trace of the gel had gone, and the tanks had a completely different temperature distribution. Broadly, this may be described as successive strata at

approximately the same temperature across the tank. Temperature distribution of a typical tank is shown in Fig 3. The surface layers had temperatures of 51° to 58° F, again in accordance with prevailing air temperatures. (Daily minimum temperatures at the time were 46° to 49° F, and daily maximum temperatures 55° to 58° F.) Temperatures a few feet below the surface were several degrees higher, and in general lay between 60° and 66° F. In the large tank (oil 34) it was noticeable that temperatures on the centre line and beneath the inner ring of manholes were higher than those beneath the North outer manhole. The mean temperature for the previous August was 60·6° F (mean maximum 65·7° F: mean minimum 55·5° F). For the first ten days of September the corresponding temperatures were 59°, 64°, and 54° F. It is therefore apparent that the oil temperatures, a few feet below the oil surface, had not dropped substantially from the high levels they must have attained during August. Below this warm zone there was a steady drop at all parts of the tanks to minimum temperatures at the bottom of the tanks. These bottom temperatures were, at, or only a few degrees above, the maximum temperatures of the bulk of the oil in the previous March.

A brief inspection of one tank (oil 22) was made on 2 October 1956. The oil was still fluid, and the bulk of it was at 53° to 55° F, roughly the same as mean air temperatures for September 1956, with slightly colder oil in the lower part of the tank and at some

TABLE III

Condition of a Stock of Oils, 22, 23, 27, and 34 in March 1955

Oil No	22	23	27	34
Viscosity Redwood 1 sec	180	196	205	195
Surface temperature, ° F	43–48	46–17	43–49	45–47
Thickness of gelled layer, ft	2–3	3–4	4–5	3–4
Temperature of gelled layer, ° F	39–43	39–45	43–47	40–47
Temperature of fluid oil beneath gelled layer, ° F	49–51	50–53	54–57	54–55
As received pour points, ° F:				
(*a*) At depot	35–40	45	40–45	40–45
(*b*) At AOL	35	35	40	45
Remarks				12,000-ton tank crust about 2 ft below surface

places near the surface. Daily air temperatures were not obtained on this occasion.

The fourth visit in May 1957 was spread over a longer period than the previous ones, and the seasonal rise in air temperature was well under way (Fig 1). But there was a short cold period immediately prior to and during the first three days of the visit. Depot staff stated that the surface of the oil had been fully gelled during each winter it had been in store. This gel could no longer be detected at any level in May 1957. Air temperatures during April 1957, mean 46·5° F (mean maximum 51·4°: mean minimum 41·5° F), must have been mainly responsible. These temperatures were almost identical with those of late October 1954, which brought the oil to a near gelled state. The important difference was that during April 1957 there was an average of 5·64 hours sunshine per day, whereas during the last ten days of October 1954 there was an average of only 2·47 hours per day and the " hot house " effect of sun on the metal roofs would be very much less.

Tank temperatures were taken at intervals of 9 feet (in one tank 6 feet) from the surface to the bottom

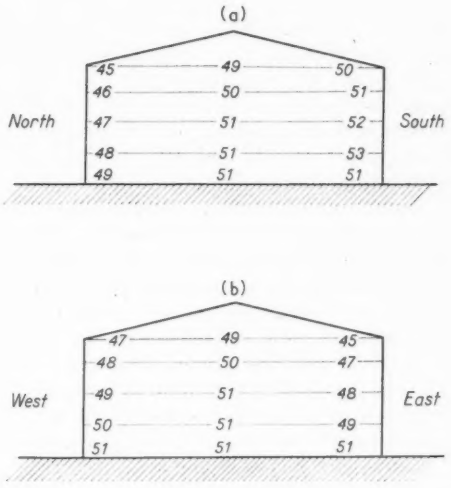

FIG 4
TEMPERATURE DISTRIBUTION, °F
(Oil 22—May 1957)

(Fig 4). Surface temperatures lay between 49° F and 57° F, *i.e.* similar to air temperatures prevailing at the time. The temperatures, 9 feet below on the centre line, under South manholes (Fig 4 (*a*)), or under the inner ring of manholes in the tank (oil 34) lay between 51° and 56° F. Beneath the North manholes, temperatures at this level lay between 46° and 49° F. Near the bottom of the tanks the temperatures varied between 49° and 52° F on the centre line; under the North manholes the range was 45° to 47° F. Temperatures across a tank, at any depth, varied by 4° to 6°, except in oil 34, where they varied by up to 10°. It is considered that during the winter the tanks would contain cold gelled outer crusts, extending down the side as well as over the top, and warmer oil throughout the bulk of the tanks. The temperature distribution in May appeared to be an intermediate stage between this condition and the distribution to be expected in the height of summer.

The last visit was made in September 1957, when the oil was being transferred to tankers for use during Fleet exercises. Temperature surveys of the two tanks (oils 22, 27) found temperatures between 54°

and 60° F at the surface, 54° to 58° F about 6 feet down, and 49° to 53° F near the bottom. The difference of temperature across either tank, at any depth, was only 2° to 3°, and the temperature pattern was the same as that found in September 1955.

During the ten days up to and including the survey, the mean air temperature was 51·5° F (mean maximum 55° F: mean minimum 48° F), with an average of only 1·6 hours sunshine per day. Surface oil temperatures were in line with the maximum air temperatures, rather than with the minimum night temperatures. During the previous August the mean temperature was 56·5° F (mean maximum 60·3° F: mean minimum 52·6° F). This pattern persisted throughout the first ten days of September, after which the seasonal fall set in. As in September 1955, the oil temperatures 6 feet below the surface in mid-September 1957 were in line with the August and early September air temperatures.

It is considered that fuels capable of gelling at winter temperatures may be expected to assume the temperature distribution shown in Fig 2 in the winter, that shown in Fig 3 in the summer, and some intermediate stage, such as that shown in Fig 4, in late spring or early summer. Fuels which do not have a tendency to gel may be expected to have the layered type of temperature distribution shown in Fig 3 throughout the spring and summer as the oil warms up. During winter it is probable that the temperatures tend to even out as the oil cools.

Observations on other oils have supported these conclusions. The oil 41, used in the second major pumping trial described by Davenport and Russell,[2] was transferred in October 1955 at 55° F to the tank selected for the trial. The tank was filled to a depth of 10 feet, less than one-third its capacity. At the time of the trial in February 1956 temperature measurements were made using thermocouples. Beneath the outer ring of manholes the oil was gelled at temperatures of 39° to 42° F. At the tank centre, and beneath the inner ring of manholes, surface temperatures were 39° to 41° F, but some 4 to 5 feet below the surface a thermocouple indicated oil at 48° to 50° F at various levels to the bottom of the tank. Prevailing air temperatures at the time were 43° to 45° F, and had been below 30° F about a month before the trial. Oil issuing from the tank during the pumping trials came out at 49° F, in agreement with the bulk temperatures indicated by the thermocouple, and only 6° F below the temperature at which the tank had been partially filled. The flow point of this oil was 55° F. Another oil, 24, transferred from one tank to another in the autumn and, inspected four to five months later, behaved in a similar manner, although it was much less liable to gel.

The summer type of temperature distribution has also been seen on a number of occasions. The outstanding example was that of oil 40. In September 1956 this tank was found to have the type of temperature distribution shown in Fig 3. Temperatures near the surface were 60° F, decreasing steadily with increasing depth to 48° to 50° F at the bottom of the tank.

Oils which do not gel have been found to exhibit the summer temperature pattern when neighbouring tanks of other oils are still in a confused state intermediate between winter and summer conditions. Thus at the time (early May 1957) when oils 22 and 23 had a temperature pattern shown in Fig 4, the low pour point oils 3, 4, and 6 in the same depot had nearly reached the condition shown in Fig 3. Oils 26, 32, and 33 were found to have the Fig 4 configuration in May 1956.

The lowest bulk temperature found was 36° F with oils 1 and 7 in February 1955. This was approached by the other low pour point oils examined during winter months. In early March 1959 centre/centre, *i.e.* samples taken half-way down the centre line, samples of oils 8 and 14 had temperatures of 38°, whilst oils 9 and 10 were only 39° and 40° F. None of these oils contained any gelled layers, but oil 10 was showing signs of wax separation. Oil 11 had a 3-foot crust of thick oil containing separated wax, whilst its centre/centre temperature was 43° F.

6. SAMPLING FOR RHEOLOGICAL MEASUREMENT

The object of sampling is to remove from any required part of the tank a portion of the oil with the minimum amount of shearing, prior to the viscosity or other determinations which are to be made.

An apparatus known as the Nash's Pot was at one time widely used in Admiralty storage depots. This suffered from the disadvantage that it was lowered into the oil open and then closed at the required position. In gelled or semi-gelled oil the top layers could be carried down with the pot, and the resultant sample would not be representative of the layer being sampled.

The standard IP sampling can [7] was then tried. Although satisfactory with homogeneous low viscosity fuels, difficulties were encountered in cold furnace fuel oil, especially when the outer layers were in a gelled or semi-gelled condition. The strength of these outer layers can be judged by the fact that a brick rested on the surface of a tank of oil 27 for several months during one winter. Under these conditions the sampling can must be weighted in order to penetrate these upper layers of oil. If the closing cork was only lightly pressed in it had a marked tendency to come out when being lowered even before the can reached the surface of the oil. The oil surface on the centre line of a tank is at least 15 feet, and may be 40 feet, below the sampling access hole. On the other hand, if the cork is pressed in too hard the oil pressure and

the viscous oil drag on the line prevents the can opening when taking samples several feet below the oil surface. Cans with narrow necks cause overmuch shearing of the oil when sampling at a depth, whilst cans with large openings render the manipulation of the corks more difficult.

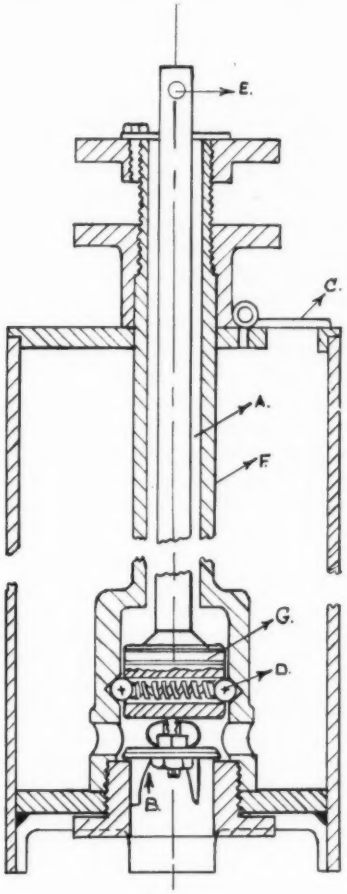

FIG 5
ADMIRALTY SAMPLING POT

With these difficulties in mind, an apparatus was developed at the Admiralty Fuel Experimental Station and is based upon a counterbalanced piston system. A sketch of the apparatus is given in Fig 5. The principle on which this apparatus works, as the sampler is lowered down the tank, is that oil flows into the annulus (*A*), formed by the piston shaft (*E*) and the piston housing (*F*), thus the pressure exerted on the piston (*G*) is equal to the upthrust of the oil on the adjustable valve (*B*). The piston (*G*) is held in the closed position by means of two spring-loaded ball bearings (*D*). The sampler is lowered into the oil by means of a cord and when the desired sampling position is reached a jerk on the cord releases the ball bearings (*D*) and the upthrust of the oil opens the valve (*B*); the increase in pressure in the body of the sampler then opens a flap valve (*C*) and the air escapes, thus giving a positive indication that the sampler is being filled. On raising the sampler after filling, both the valves (*C*) and (*B*) automatically close, thus ensuring that no adulteration of the sample occurs on passing through the top layers of oil.

This type of sampler was quite satisfactory in the earlier work, but with the advent of coni-cylindrical viscometer determinations it was realized that the filling orifices, like those of the IP sampling can, were too small, and in filling the containers the oil would be subjected to a considerable amount of shear. To overcome this difficulty several modifications to the above apparatus were made, and the work resulted in a sampling device which was not only more satisfactory for this work but was also easier and cheaper to produce. This apparatus is shown in Fig 6. The body of this apparatus was made from brass tubing $3\frac{3}{4}$ inches in diameter and had three ports in the side 3 inches long and 1 inch deep, which were closed by the piston itself. The piston was held in the closed position by three spring-loaded ball bearings. In order to prevent the piston turning and to centralize the spring-loaded balls in their grooves, the shaft was made of $\frac{1}{4}$-inch square steel rod. In order to counterbalance the upthrust of the oil on lowering the apparatus into the tank, the piston shaft was centralized by a webbed cover, as shown in Fig 6. Again the operation of this device depends upon the release of a ball bearing from its groove by jerking a cord or chain.

The design of sampler has the advantage that it can be made to open either at the top or the bottom. If a top opening is desired the piston can be made of solid material, but in the case of a bottom-opening device a flap valve must be fitted into the piston to allow oil to enter the body of the sampler.

Even lower shearing of the sample may be achieved if the sampling pot were so designed as to be capable of forming the non-rotating cylinder of the viscometer, but this so far has not been attempted. Alternatively, one could employ some form of viscometer which could be operated *in situ* in the tank. Ackroyd designed an immersion viscometer,[8] but it suffered from the disadvantage that it operated as a rotating cylinder in an " infinite sea of oil " and gave results which were too high as the applied shear stress approached the yield value of the oil.

The selection of correct sampling points requires due care. A first approximation was to take centre/centre samples and assume that they would be representative of the largest volume of oil in the tank. If the study is limited to one sample per tank this must be the best position to select. It is useful to have an additional sample from side/centre, *i.e.* halfway down one side of the tank, usually centrally

beneath a manhole and approximately about 2 feet from the tank wall. A better procedure is first to take a temperature survey, so that samples can then be taken from the hottest and coldest parts of the tank.

The properties of these fuels depend, as has been shown in an earlier paper, on both time and temperature. If the fuel oil is brought to a given temperature

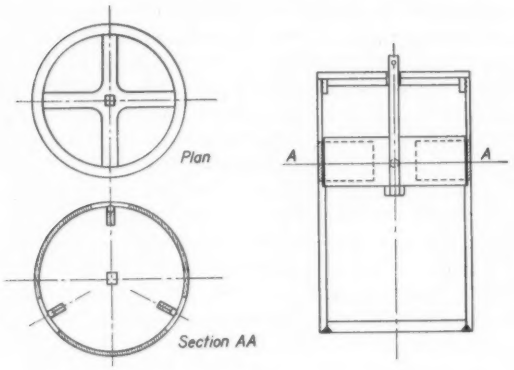

FIG 6

MODIFIED ADMIRALTY SAMPLER

from a higher temperature it will not develop its maximum structure and apparent viscosity at once, but will thicken over days or months. Likewise, if it is brought to this temperature from a lower temperature it may already be considerably more viscous than it might ever become by long standing at this temperature. Ackroyd [3] has shown that for any given temperature in the annual temperature cycle, fuels, in storage, had the highest viscosities in the spring when they were warming up, and the lowest in the autumn when they were cooling down.

The same reasoning can be applied to oil in various parts of the same tank. Thus, in the spring, oil near the top of a tank can be expected to warm up more quickly than oil near the centre, and in consequence to contain more residual structure. In the autumn oil at the top may be as cold, if not colder, than oil near the bottom, but as it will recently have been warmer, it cannot to be expected to be as viscous as oil near the bottom. These differences have been observed.

In the light of these possibilities the following procedure is recommended:

(*a*) Find the temperature distribution in the tank, using a distant reading thermometer if one is available.

(*b*) Take samples from the centre/centre and from the warmest and coldest parts of the tanks, to cover the bulk of the oil and the possible extremes.

(*c*) Consider the results in the light of the probable thermal history of the various zones.

This would be a thorough, but time-consuming process. If time is short, therefore, it may be necessary to omit the temperature survey, take samples from bottom North side, centre/centre, and top South side and note the temperature and condition of each sample.

7. EXAMINATION OF THE SAMPLES AND INTERPRETATION OF THE RESULTS

The "IP maximum" and "as received" pour points of some of the oils have been determined at the depots, and these may be interpreted in the normal manner, as may also any other standard laboratory inspection data. In addition to these tests, yield values of the oil have been determined, but it is considered that the results obtained may be too low because of the work done on the sample in filling the narrow bore yield value tubes.

Since the emphasis progressed towards the determination of a viscosity in a coaxial cylindrical viscometer, this type of test under suitable conditions has become the main and, in some cases, the only determination attempted on the site. In order to minimize the changes in structure between sampling and measurement, it is now considered that the changes in temperature of the oil should be kept to an absolute minimum. In order to maintain this condition it is preferred to work at the storage site if possible. By doing this, the sample of oil in the sampler can be transferred into a conditioned wide-necked thermos jar on top of the tank and then tested with the minimum delay in an improvised laboratory on the site. Some work, however, has been done on samples packed in thermos flasks contained in heavily lagged boxes and then transported to central laboratories.

The relative merits of constant shear stress and constant rate of shear instruments have been discussed in an earlier paper.[1] The authors have employed one type of constant shear stress apparatus capable of operation from 50 up to 1000 dynes/cm^2. This is simple to operate but must be constantly attended, particularly when the rate of shear exceeds about 20 sec^{-1}. The most useful constant rate of shear apparatus for general purposes is considered to be the Ferranti portable viscometer. This can be operated at a range of rates of shear by varying the inner and outer cylinders; also three speeds can be selected, giving three rates of shear for each pair of cylinders. The major limitation is that if the force exerted by the viscous drag is too great the needle will be deflected too far and will be off scale; in other words there is a band of viscosities which can be measured at each rate of shear, and the range of usable shear rates for any one sample is limited.

The conditions under which the instruments are operated are bound up with the interpretation that is placed on the results. Billington has discussed the probability that after continued shearing the oil will be reduced to a constant viscosity with no residual structure. Other workers visualize a building-up process as exercising some control after prolonged shearing. In the full-scale pumping trials it was found that after shearing for some time, which might be minutes or several hours according to the state of the oil and the shearing conditions employed, the rate of decrease of apparent viscosity with time slowed down. The term " equilbrium viscosity " was used to describe the condition when the viscosity appeared to be reaching a constant level. It was, however, not a well defined state and an absolutely constant viscosity tended to be very difficult to attain; different workers had different ideas as to what was meant by equilibrium viscosity. For the purpose of this paper the term is employed and is defined as the level of viscosity at which the rate of decrease of viscosity with continued shearing has decreased to 10 per cent per hour.

Consider now a tank of oil which has to be tested using coaxial cylinder viscometers to decide the rate at which it can be pumped. The shear rates in the pipelines corresponding to various flow rates and the shear stresses corresponding to full, half-full, or near-empty tanks, will be calculable. If the level of oil in a tank falls 32 feet the pressure exerted by the head of oil falls 13 psi, *i.e.* more that the total suction which can be exerted by the average pump, therefore viscosities should be measured over a range of shear stresses. One essential precaution is to remember to make some allowance for the force required to get the oil through the swing arms and tank valve. In a trial with oil 27 it was found that this force was equivalent to a pressure drop of 2·9 psi.

If the available shear stress is of the same order or even less than the yield value of the oil, no worthwhile pumping rates can be expected. It is even possible that the empirical use of equilibrium viscosity to calculate pumping rates might be unsatisfactory. It would, then, be unwise to decide whether pumping can occur from equilibrium viscosity determined in constant rate of shear viscometers, since in shearing the oil down to this condition the viscometer may exert greater shear stresses on the oil than those available to pump it. A constant shear stress viscometer would not measure yield value once the oil had been disturbed by sampling, but should indicate whether breakdown would occur in a reasonable time with forces available.

Having ascertained the temperature and condition of the oil in a tank, the time taken to empty the tank without applying heat will depend on the way in which it is pumped. The thickest oil should be moved first, while the maximum head of oil is available to shear it down. In wintertime this implies that once pumping from the fluid oil is under way some attempt should be made to draw off the thick outer layers while the tank is still fairly full. Conversely, in summer it is wiser to take the coldest oil in the bottom half of the tank early and not remove the thin layers from the top and leave the thicker oil to be moved with a reduced head of oil.

8. CONDITION OF TYPICAL FUELS IN STORAGE

During the period of this investigation the majority of fuels in storage consisted mainly of Schedule 390-A uels, which have a Redwood 1 viscosity not exceeding 200 sec at 122° F. Many of these fuels had been purchased before the introduction of the Schedule 390-A specification, but they were re-classified when they complied with the Schedule 390-A specification. Owing to the flow point/viscosity requirement in the specification, some fuels with viscosities between 200 and 300 sec Redwood 1 and purchased under the Schedule 390 specification could not be re-classified. These are, in the main, low pour point fuels. In addition, there are a few fuels remaining in store which had been purchased prior to these specifications and do not satisfy these specification requirements.

In view of the well-known thixotropic properties of furnace fuel oils, few estimates of their viscosity in the range 35° to 60° F are quoted in the literature. One is, however, given in " Modern Petroleum Technology " [9] to illustrate the behaviour of typical fuels. The viscosity–temperature curve corresponding to a 200-sec fuel is reproduced with viscosity in poise in Fig 7. This curve appears to make some allowance for the development of " structure." This is not so with a viscosity calculator supplied to customers by a well-known fuel supplier, as shown in the lower curve in Fig 7. Coaxial cylinder viscosity data in Fig 7 for the oils at 25° F flow point or less has been interpolated whenever necessary to give probable equilibrium viscosities under a shear stress of 150 dynes/cm^2. Almost all fall around the above two reference lines. The exceptions are four Schedule 390 fuels having Redwood viscosities greater than 250 sec at 122° F, and oils 3 and 18.

These 390 oils could not reasonably be expected to come within the reference lines, but oil 12 departs sharply from all the others. This oil is of a type which is known to thicken rapidly at temperatures well above its flow point. The new Method XV heat treatment was designed to simulate the storage viscosity of this oil, as well as for other " more normal " oils. Oils 3 and 18 have been seen only once, because the former has been disposed of and is no longer available for study, and the latter was examined only shortly before the preparation of this paper, and it is proposed to study it further. One other point worthy

of mention is that samples from the upper layers of oil 10 were much more viscous than the bulk oil, owing to the flotation of separated wax. This oil had been in store only about a year, and experience with similar oils elsewhere suggests that the wax-thickened layer will slowly become less deep but more viscous.

Oils having a flow point of 30° F merit special mention, as these are permitted to have the highest value of Redwood viscosity at 122° F laid down by current specifications. Oils 19, 20, 21, and 24, four deliveries from the same refinery at about 160 sec Redwood, appear to thicken faster than the best low flow point oils, but at worst have equilibrium viscosities at 150 dynes/cm² of about 10 poise at 48° F. Limited data from one recent visit to oil 25 gave it viscosities of about 20 poise at 32° F. This is from the same source as oil 18 and is stored in another tank in the same depot. It also will be investigated further.

The remaining two oils in this flow point group were part of a consignment received from a Middle East refinery from which the Royal Navy does not normally obtain fuel. This consignment gelled on the surface in the winter months during storage in a U.K. depot to such an extent as to be able to support a brick. The viscosity data of these fuels are shown in Fig 8. The temperature distribution of the oil in these tanks was examined in some detail and is discussed in Section 4. Owing to the jacketing effect of the gelled oil, average temperatures in the tanks never fell below 48° to 50° F, but on occasions colder oil existed in the outer layers. It has therefore been possible to construct a viscosity/temperature chart down to 40° F. At temperatures below 50° F an applied shear stress of 150 dynes/cm² was, on a number of samples, not sufficiently far above the yield point of the oil for rapid breakdown, hence the high apparent viscosities were obtained. A shear stress of 250 dynes/cm² caused more rapid breakdown, and figures at this shear stress are quoted for comparison.

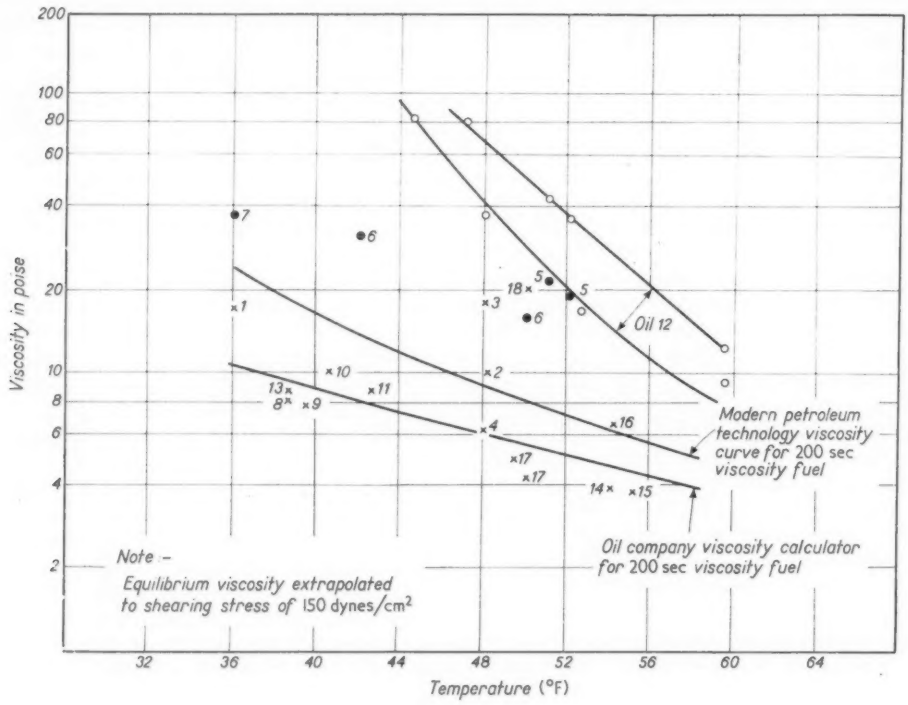

FIG 7

EQUILIBRIUM VISCOSITY/TEMPERATURE CURVE FOR OILS 1 TO 18 INCLUSIVE

The remaining two oils in this flow point group were part of a consignment received from a Middle East refinery from which the Royal Navy does not normally obtain fuel. This consignment gelled on the surface in the winter months during storage in a U.K. depot to such an extent as to be able to support a brick. The viscosity data of these fuels are shown in Fig 8. The temperature distribution of the oil in these tanks was examined in some detail and is discussed in Section 4. Owing to the jacketing effect of the gelled oil, average temperatures in the tanks never fell below 48° to 50° F, but on occasions colder oil existed in the outer layers. It has therefore been possible to construct a viscosity/temperature chart down to 40° F. At temperatures below 50° F an applied shear stress of 150 dynes/cm² was, on a number of samples, not sufficiently far above the yield point of the oil for rapid breakdown, hence the high apparent viscosities were obtained. A shear stress of 250 dynes/cm² caused more rapid breakdown, and figures at this shear stress are quoted for comparison.

It was estimated that after long storage the equilibrium viscosity of the better of these two oils might be expected to lie between 40 and 100 poise under a shear stress of 150 dynes/cm² and 25 and 60 poise under 250 dynes/cm². The lower figures would be expected from oil that had only just cooled down from temperatures above 48° F, or was well protected from rapid cooling, *i.e.* upper layers in autumn or bulk in winter. The higher figures would be expected from outer layers in winter or early spring. No constant rate of shear measurements were made on this oil at the depot, but portions of a 40-gallon sample brought back to the laboratory from the lighter oil and stored in a refrigerator at 48° F for one to six weeks had apparent viscosities of 23 to 31 poise after 30 minutes

shearing at a rate of shear of 9·7 sec^{-1}. It was not possible to arrange a pumping trial at the depot. The behaviour of this oil 22 in the pumpability rig is discussed in the next paper.

Warming this oil to 115° F for a pour point determination, or to 165° F prior to the flow point test, completely destroys the structure built up in storage, and it is not easily re-formed, except by storage. The " as received " pour points of the oil in these two tanks were 35° to 40° F and 40° to 45° F, yet the flow points were only 30° F. Viscosity measurements on the stored oil at low shear stresses or shear rates would new test. As already stated, this oil is the only one known to behave in this manner, and, moreover, is from a source not normally used by the Royal Navy, hence its behaviour is not by itself regarded as a valid objection to the use of the test with the range of oils normally purchased.

Several oils of 35° or 40° F flow point have been examined. In this range the permissible Redwood viscosity at 122° F is restricted to 175 sec. Oils 28, 29, 31, and 35 are from the same U.K. refinery as oils 19, 20, 21, and 24 and, like them, did not thicken excessively in winter storage. Some of the extensive

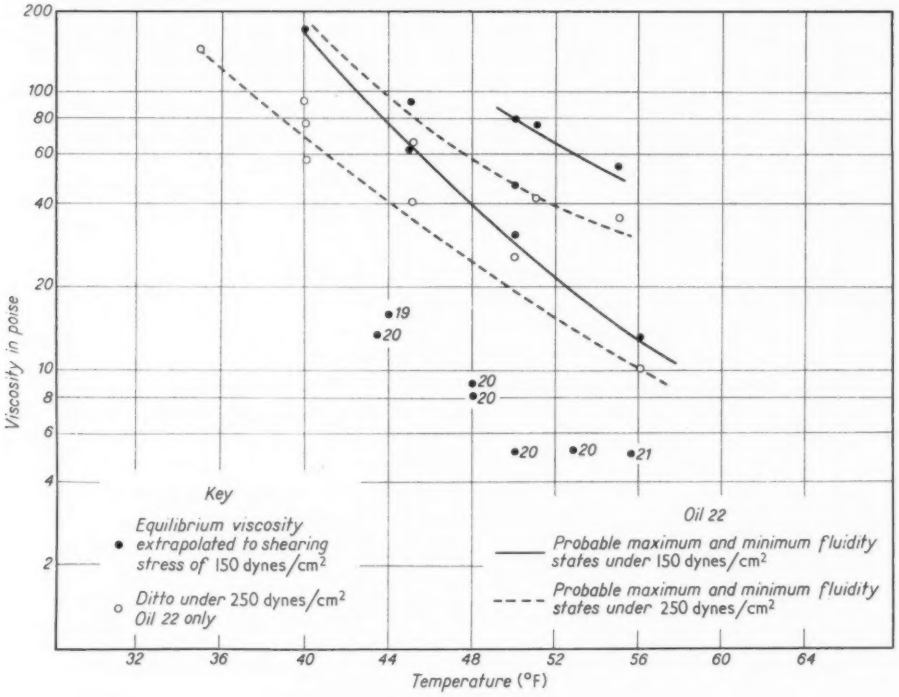

FIG 8

EQUILIBRIUM VISCOSITY/TEMPERATURE CURVE FOR OILS 19 TO 25 INCLUSIVE

be expected to be much above those on heat-treated oil. One extreme example was afforded by some viscosity determinations at 40° F, when under 150 dynes/cm² the stored oil gave equilibrium viscosities of 180 poise or more, as compared with about 40 poise for oil subjected to an early version of the new Method XV test. At temperatures more typical of bulk oil temperatures and using rates of shear equivalent to those now demanded for quick fuel transfer, the discrepancies are very much less. With the cylinders and conditions proposed for the new pumpability test using the Ferranti viscometer (*i.e.* a rate of shear of 9·7 sec^{-1}), the stored oil may be expected to have a viscosity of not more than twice that given by the data available are shown in Fig 9, again in terms of a constant shear stress of 150 dynes/cm². One of these oils, 35, has been found by Ackroyd not to have attained the viscosity level predicted by Method XV even after two years storage, unlike oil 22, which attained a higher viscosity level in its first year of storage.

Oils 26, 32, and 33 came from another U.K. refinery. An early version of the proposed pumpability test was tried on these oils and gave satisfactory results. These were transferred down a pipeline having an exceptionally long delivery line and short suction. Passage through the pumps sheared all the structure out of the oil and reduced the viscosity to about 6

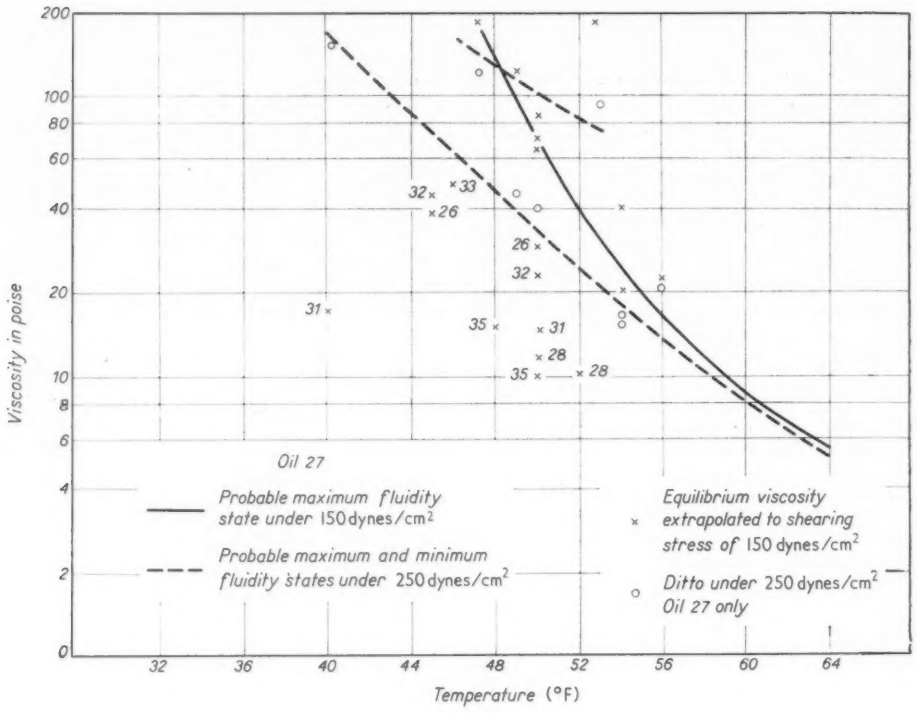

FIG 9

EQUILIBRIUM VISCOSITY CURVE FOR OILS 26 TO 35 INCLUSIVE

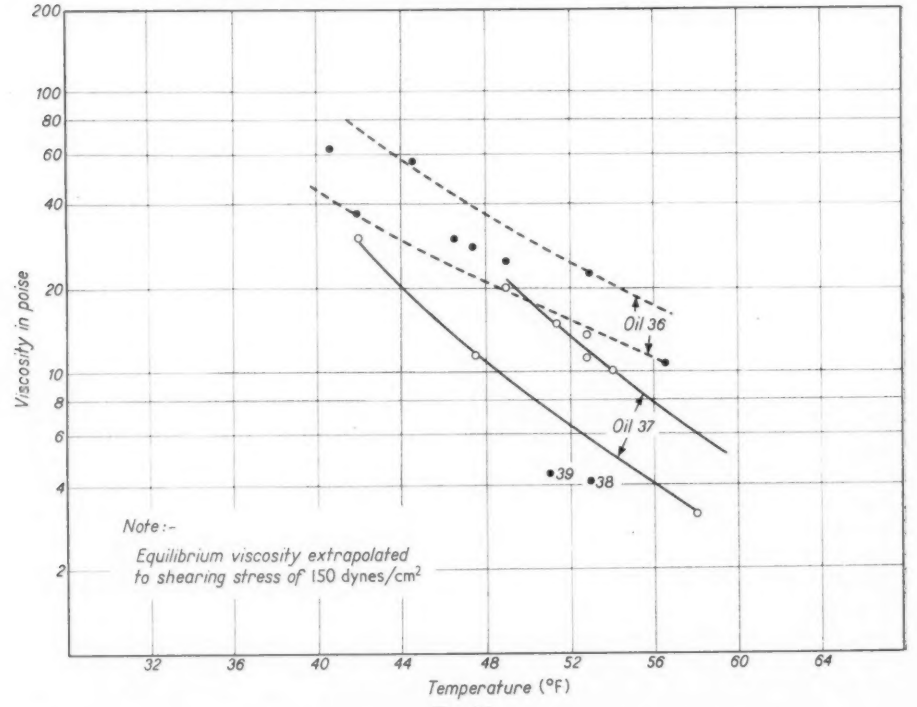

FIG 10

EQUILIBRIUM VISCOSITY/TEMPERATURE CURVE FOR OILS 36 TO 39 INCLUSIVE

poise at 50° F. After standing undisturbed overnight, or flowing down the pipeline for about 20 hours under a shear stress of 100 dynes/cm², the oil recovered some of its structure and attained an equilibrium viscosity of about 9 poise at 50° F under this shear stress.

Oil 30 is a much lower viscosity oil than is normally supplied at this flow point and has been in stock for over 20 years. It is not representative of present purchases, and is only of interest as one of the oils used in the first full-scale trials. Of more interest are two higher flow point oils from the consignment, of which oils 22 and 23 were the more fluid members. These oils, 27 and 34, fail the requirements for Schedule 390-A or 390 fuels. A brief pumping trial was possible with oil 27 in September 1957. The line was fitted with pressure gauges at either end of the suction pipe, and pumping started as would normally take place in a depot. Once steady flow conditions had been established at 56° F, shearing stress was 380 to 390 dynes/cm², rate of shear 8·5 to 8·6 sec^{-1}, and pipe viscosity 44 to 46 poise. The equilibrium viscosity given by coaxial cylinder viscometers was 20 to 23 poise. This discrepancy was evidence of the possibility that pipe viscosities may be as much as twice laboratory equilibrium viscosities. It also confirmed the high viscosity level of these oils as compared with most other supplies.

Only one oil of 45° F flow point, and one of 50° F flow point, have been examined frequently. Neither would meet current specifications. One, oil 36, was an off-specification batch from the U.K. refinery which produced oil 35; the other, oil 37, was purchased before present specifications were introduced. Both were included in the large-scale pumping trials conducted in 1954 and 1955, and the bulk of the measurements since then fall within the scope of Ackroyd's paper. To complete the survey, typical results on both are set out in Fig 10. Oil 37, with its low viscosity at 122° F, rapidly decreases in apparent viscosity at temperatures above 50° F. Few oils have been offered against specification at either flow point. Recently, two consignments (38 and 39) of 50° F flow point and 90 sec Redwood, have been inspected in July 1959 after less than one year's storage. Typical viscosities using the Ferranti viscometer were 5·8, 4·3, and 3·4 poise at respective rate of shear of 1·8, 6·8, and 18·8 sec^{-1} all at 55° F, with no rapid breakdown under shear.

Three oils well outside specification limits have been studied. Oil 41, with a flow point of 55° F and Redwood viscosity of 164 sec, came from a U.K. refinery and was used in the February 1956 pumping trials. The others, 40 and 42, both had flow points of 70° F. One was selected for the 1954 and 1955 co-operative pumping trials. All three are well outside specification limits and well outside requirements for oils which may be stored unheated, and no viscosity/temperature graphs have been prepared for them. Most of the available information on oils 40 and 41 is to be found in the paper which describes the Panel's full-scale pumping trials. Oil 42 was seen once in April 1957, when at 53° F it gave equilibrium viscosities as follows:

At 250 dynes/cm²	250 poise
375 ,,	170 ,,
500 ,,	50 ,,
700 ,,	32 ,,

The final point to be considered is whether there is any significant difference between the condition of oils stored in constant temperature storage, *i.e.* underground, and those stored in conditions where the temperature may vary, *i.e.* in above-ground tanks. No oils have been deliberately stored partly underground and partly in above-ground tanks, the handling of stocks being essentially a matter of operational convenience. Reliable evidence is therefore hard to obtain. In some instances, however, oils apparently of similar characteristics received from the same refinery have been laid down in more than one store, and out of a series of deliveries some have been stored above-ground and some underground.

The low flow point oils 1, 2, 3, 8, 9, 10, and 11 shown in Fig 7 have counterparts in underground storage. The comparison is as follows:

	Underground	*Tank Storage Viscosity Deduced from Fig 7*
Oil A	8 to 10 poise at 54° F	
,, B	8 to 12 ,, 53° F	4 to 7 (oil 3 probably 12) at 53° F
,, C	5·5 to 6 ,, 50° F	5 to 9 (oil 3 gave 16) at 50° F
,, D	11 to 12 ,, 47° F	6 to 12 (oil 3 probably 20) at 47° F

Oils B and D both had a marked tendency to separate wax, which eventually concentrated in the upper few feet of the oil and made reliable sampling very difficult in the intermediate stage. Oil B has been pumped when it flowed down the pipe at a uniform pipe viscosity of 5·5 poise.

U.K. refined oils 16, 17, 19, 20, and 21, all from the same refinery, have their counterparts in underground storage as follows:

	Underground	*Tank Storage Viscosity Deduced from Figs 7 and 8*
Oils E and F	4·5 to 5·5 poise at 53° F	
Oil G	6·3 to 6·7 ,, 47° F	4 to 6 poise at 53° F
,, H	4·8 to 5 ,, 47° F	5 to 12 poise at 47° F
,, I	10 to 14 ,, 47° F	

Three of these have been pumped, oils E and F at a pipe viscosity of 3·5 to 4 poise, and oil I at a pipe viscosity of 11·5 poise.

Portions of oils 3, 14, and 15 were transferred underground and bulked in the process. The mixture had viscosities of 6 poise underground at 46° F which is within experimental error, the same as would have been expected from the measurement made when it was in tank storage.

There is no significant difference between the condition of oils of these types whether stored above or below ground, probably because all have good storage

characteristics at temperatures above 45° F. Some oils having flow points 35° to 45° F and Redwood viscosities at 122° F of 90 to 110 sec have also been examined. These came from the Middle East refinery, which supplied oils 37, 38, and 39. We have

	Underground	*Tank Storage Viscosity Deduced from Fig 10*
Oil J	4 to 7 poise at 53° F	
,, K	5 to 9 ,, 53° F	5 to 12 poise at 53° F
,, L	5 to 7 ,, 52° F	

Oils J and K were pumped at pipe viscosities of 3 and 4 poise. This group of oils appears to lend support to the contention that in constant temperature storage oils are not likely to build up as much structure as under varying temperature conditions.

The only other types of oil examined were two lots of mixed oils, mainly of the type represented by oils 18 and 25. The evidence available on this type of oil in above-ground storage is as yet extremely limited, and therefore no useful comparisons can be drawn. It is considered that reliable conclusions as to the difference between the two types of storage can be obtained only by storing in both types of storage some of those oils known to thicken rapidly at temperatures of 50° to 55° F. As the object of the proposed specification is to avoid the purchase of such oils, this exercise does not appear to be likely to take place.

CONCLUSIONS

(1) A survey of temperature of the oil in the tank should be the first step in an examination for probable pumpability.

(2) Three distinct types of temperature distribution in unheated tanks may be expected, according to the season of the year and the nature of the oil.

(3) Samples for viscosity determination in coaxial cylinder viscometers should be taken from the centre of the tank and from zones where the preliminary survey indicates that there may be oil of different viscosity.

(4) Where time does not permit a temperature survey, samples from the tank centre, bottom North side, and top South side should give a useful indication of the range of viscosity and temperature in the tank.

(5) The new type of positive action sampling pots similar to the one described should be used.

(6) When applying the method for predicting pumpability from equilibrium viscosities, which has been described in earlier papers, some allowance should be made for loss of pressure in swing arms, tank valves, and the presence of layers of oil of different viscosity.

(7) When substantial amounts of oil of different equilibrium viscosity exist in a tank it is essential for maximum pumping rates to remove the most viscous fuel as soon as possible while maximum head of oil (hence maximum shearing stress) is available.

(8) Examination of a variety of oils in store has shown that the flow point and Redwood viscosity clauses in current Royal Navy specifications have given a substantial though not a complete protection against the purchase of unpumpable fuels. Flow point clauses cannot be expected to rate fuels in order of pumpability.

(9) Although it is anticipated that fuels in constant temperature storage (*e.g.* underground) will not develop such high viscosity as fuels exposed in above-ground tanks to seasonal variations of temperature, the available evidence mainly relates to fuels which do not develop a high viscosity level in either type of storage.

ACKNOWLEDGMENTS

The authors are indebted for permission to publish this paper to the Board of Admiralty, who are not, however, responsible for the opinions expressed. The large volume of work at the oil fuel depots which it represents has only been possible with the assistance of various members of Admiralty Fuel and Lubricants Advisory Committee, Panel F, of the authors' colleagues at the Admiralty Oil Laboratory, and of depot staff.

References

1 " The Measurement of Flow Properties by Coaxial Cylinder Viscometers," this symposium.
2 Davenport, T. C., and Russell, R. J. " The Full-Scale Pumping of Admiralty Fuel Oil and its Relation to Laboratory Tests," this symposium.
3 Gill, F., and Russell, R. J. *Industr. Engng Chem.*, 1954, **46**, 1264.
4 Ackroyd, G. C., Hosking, D. E. M., and Lowe, A. G. " The Development of a Test to Predict the Pumpability of Admiralty Furnace Fuel Oil," this symposium.
5 E-in-C Specification No. 0–1, dated 2 December 1953.
6 E-in-C Specification No. 0–1A, dated 2 September 1954.
7 Standard Method IP51/58, Fig 4.
8 Penny, F. D., and Ackroyd, G. S. *Petroleum, Lond.*, 1958, **21**, 196.
9 " Modern Petroleum Technology," 2nd edn. London: IP, 1954, p. 493.

THE FULL-SCALE PUMPING OF ADMIRALTY FUEL OIL AND ITS RELATION TO LABORATORY TESTS *

Prepared by T. C. DAVENPORT † and R. J. RUSSELL † (Fellow) and presented by T. C. DAVENPORT

INTRODUCTION

THE Royal Navy has to maintain large stocks of fuel oil available for an emergency. This fuel is of necessity stored for long periods in unheated tanks. It may also have to be pumped cold. Long period unheated storage of this type has long been thought to induce the maximum amount of gel structure in a fuel oil, and thus to increase the likelihood of serious pumping problems. Therefore in 1951 the Admiralty Oil Quality Committee (now the Admiralty Fuels and Lubricants Advisory Committee) set up Panel F to investigate the pumpability of fuel oils in Admiralty storage and to develop a rapid laboratory test to predict the pumpability of Admiralty fuel oil.

As a result of the Panel's early laboratory work, the Method VII flow point test [1] was introduced into the Admiralty specification [2,3] in 1953 as an interim measure. When the flow point test was produced there was no knowledge of the pumping performance of Admiralty fuel oils. Also there was little theoretical or experimental knowledge of the structure developed by storage in fuel oils which contained both wax and asphalt. Therefore it was necessary to measure the actual flow properties of a selection of Admiralty fuel oils after storage to provide the basic data with which to assess any predictive pumpability test. This was first attempted by taking samples of stored fuels and sending them to a number of co-operating laboratories so that their yield values and viscosities [4] could be measured. The different laboratories reported widely differing results. It was also found that, although depot transfers of some oils indicated that they were almost unpumpable, laboratory tests on samples indicated that reasonable flow rates should have been possible.

This difference could have been caused by:

(1) changes in the fluidity of the oil during transfer to the testing laboratories;

(2) laboratory yield value and viscosity tests with oils below their pour point not being able to predict installation flow rates satisfactorily.

The finding was only based on general experience, and more accurate data were required before the Panel could carry on with its task. It was decided that full-scale trials should be carried out to determine the flow properties of a selection of stored oils at the lowest temperatures likely to be met and to find how full-scale tests and results in laboratory instruments agree with each other. Therefore the pumping trials described in this paper were held between 1953 and 1959 to measure the flow properties of Admiralty fuel oil after storage. The storage conditions studied were:

(1) surface tanks (in which the oil temperatures vary over an annual cycle);

(2) underground installations (where the temperature is practically constant);

(3) on board ship.

The present paper is divided into four sections. Sections I and II are concerned with surface installations, Section III with underground installations, and Section IV with conditions on board ship. Finally, the overall conclusions from the work are given.

I. STEADY STATE PUMPING OF OILS AFTER LONG-TERM, UNHEATED, SURFACE STORAGE

Panel F undertook its first full-scale trials on Admiralty fuel oil in October 1953 and February 1954. In these trials the different oils were pumped through different lines. In these lines the line diameter varied between 18·00 and 13·25 inches internal diameter, 15·25 inches internal diameter being predominant. To allow for the effects of different diameter lines and to enable the full-scale results to be correlated with laboratory results, the former were analysed according to the scheme given in Appendix 1. Pressures were measured by Bourdon gauges, flow rates by tank dips, and oil temperatures by thermometers in thermowells. It proved impossible to correlate results from different test lines. Also it was found that the methods of measurement were insufficiently accurate. However, the results indicated that a valid comparison could be made only between viscosities from full-scale trials and viscosities measured in laboratory viscometers when the laboratory tests were made on the trials site.

It was decided that in future trials different oils would be pumped in the same test line as far as possible. More extensive and simultaneous test measurements would be taken by a sufficiently numerous test team to man every point. More accurate instrumentation was developed, and trials were then made in

* MS received 11 December 1959.

† The British Petroleum Co. Ltd.

October 1954, when the oils were warm, to prove the new instrumentation, preferably by showing that the pipe and laboratory viscosities were equal. The pumping circuit used was that for the subsequent cold weather trials, so that any peculiarities of the pipeline system could be found.

Since pumping difficulties in surface installations normally occur on the suction side of the pump, where the available shearing stress is limited by the maximum pump suction, a long suction pipeline was selected for

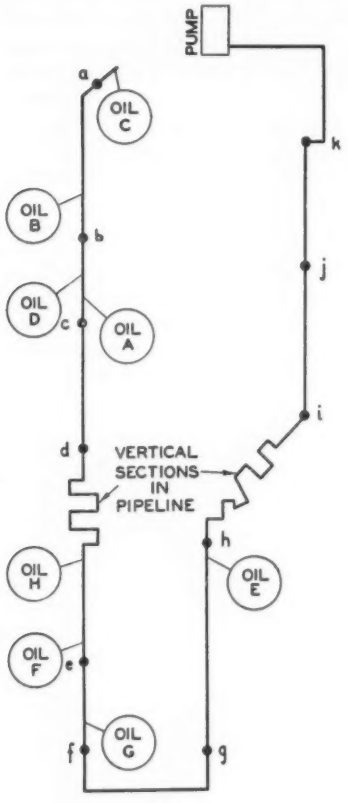

FIG 1

SUCTION PIPELINES AND SITING OF TANKS CONTAINING TEST OILS IN STEADY STATE PUMPING TESTS

the test line. It was considered that the flow properties of the oils might vary along the test line, which was therefore split into a number of short sections by test points. Air bleed cocks were fitted at all the observation points and also at the base of each tank and at high points in the line to vent any air which accumulated in the pipeline.

The depot pumps were of the three-throw, double-acting, horizontal type. The delivery line was made short so that it would not have any effect on the results. A plan showing the location of the storage tanks and pumphouse, the layout of pipeline, and the position of the instrument test points is given in Fig 1.

Instrumentation

The instrumentation was found to be just adequate for the work. It was as follows:

1. *Temperature*

The temperatures of the oils in the tanks were measured at various positions with cup case thermometers and with sample cans, using the techniques described in the "Petroleum Measurement Manual."[5] Thermometers were placed in shaded positions at all points to measure the air temperature. Since thermometers in thermowells were greatly affected by external atmospheric conditions, calibrated mercury-in-glass thermometers, immersed directly in the oil through glands to a depth of 6 inches, were used to measure oil temperatures. They were fitted at points *a*, *b*, *c*, *d*, *e*, *f*, *h*, and *j* (Fig 1). The exposed thermocouple units shown in Fig 2 were used to measure the variation of temperature across the pipes. They measured temperatures at 1, 4, 8, and 12 inches from the wall. They

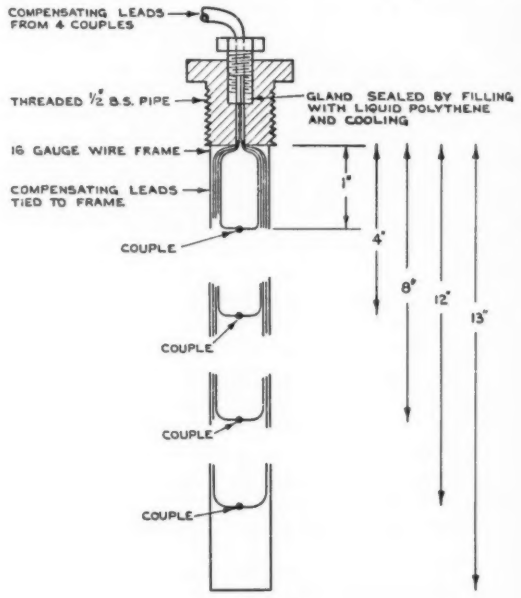

FIG 2

THERMOCOUPLE OIL TEMPERATURE TRAVERSE PROBE

were fitted vertically at points *g*, *i*, and *k* and horizontally at point *j*.

2. *Pressure*

Three types of gauge were fitted at every test point:

(*a*) Calibrated Bourdon gauges—fitted as shown in Fig 3.

(*b*) Special mercury-in-glass manometers attached to the line via a surge pot shown in Fig 3. Before taking a reading, air was pumped into the surge pot with a cycle pump to ensure that only a column of air transmitted the pressure from the

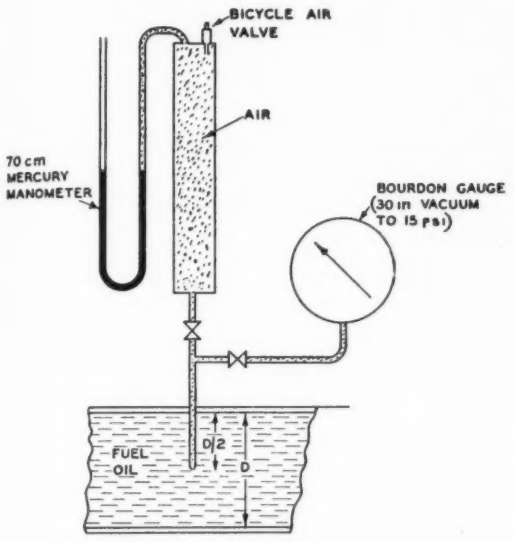

FIG 3

PRESSURE MEASUREMENT APPARATUS USED IN TRIALS

oil at the centre of the pipe to the mercury column or Bourdon gauge. Thus the oil/air interface was always at a known point, namely, the centre of the pipe.

(*c*) Magneto-inductive pressure transducers, made by Salford Electrical Instruments, were mounted in short side-arms at the top of the pipe so that the diaphragms were flush with the inside wall of the pipe. The indicating dials of the transducers were collected into three convenient groups.

The precision of the measurements was found by statistical analysis of the results of the trials and gave 95 per cent confidence limits as follows:

Transducer	±0·12 psi
Mercury manometer	±0·15 psi
Bourdon gauge	±0·20 psi

3. *Flow rate*

The October trials showed that at low flow rates dips would not be sufficiently accurate, since with very viscous oils in a tank the oil surface is not horizontal during pumping. A Brodie–Kent positive displacement flowmeter, the percentage accuracy of which was practically independent of flow rate, was therefore fitted in the delivery line. It would be by-passed if the flow rate exceeded its rated maximum of 270 gal/min. The 95 per cent confidence limits on flow rates (at 175 gal/min) were found to be:

By dip measurement	±18 gal/min
By flowmeter	± 8 gal/min

Since pressure drops of the order of 1 psi were found in the trial, the accuracy of viscosity measurement was almost entirely controlled by the pressure measurements. For a single reading it was about 25 per cent.

4. *Laboratory instruments*

Three co-axial cylinder viscometers were taken to the depot to make tests under the conditions of shear

TABLE I

Important Dimensions of Co-axial Cylinder Viscometers used in Steady State Pumping Trials

	Type of instrument		
	Constant shearing stress (Searle type)	Constant rate of shear (Couette type)	Ferranti viscometer (Couette type)
Diameter of outer cylinder, cm	8·738	4·78	4·77
Diameter of inner cylinder, cm	8·157	4·60	4·43 (A cylinder) 4·13 (B cylinder)
Annular gap, cm	0·2905	0·09	0·17 (A cylinder) 0·30 (B cylinder)
Length of inner cylinder (straight sides), cm	10·21	5·91	2·54
Half cone apex angle (inner cylinder)	39·2°	87·3°	Air gap guard ring device
Half cone apex angle (outer cylinder)	48·4°	Flat	

holding in the pipe. Two were operated at a constant shearing stress by means of weights, the third was driven at a constant rate of shear by an electric motor. The important dimensions of these instruments are given in Table I. In addition, glass and steel U-tubes were used to measure yield values.

Test Procedure

1. *Pumping*

To prevent air entering the pipeline all the swing arms in tanks not used were lowered into the oil and all valves in the side lines screwed down tightly. When changing oils, two and a half times the volume of the suction line was first pumped to remove the previous oil. The pumps were then stopped so that oil in the tank built up a positive pressure throughout the line. This sometimes took over half an hour. All venting points were then opened until all the air in the line was expelled. With some oils this took more than an hour. The pumps were restarted and the test commenced.

The test readings taken were:

(*a*) Pressure by Bourdon gauges, mercury manometers, and transducers at 0, 20, and 40 minutes past each hour.

(*b*) Temperatures by thermometers at 0, 20,

and 40 minutes past each hour. Temperature traverse measurements were made at various times.

(*c*) Flow rates. Ullages on both delivery and receiving tanks were taken at 10, 30, and 50 minutes past each hour. The totalizer reading on the flowmeter was taken at the same time. Also the quantity pumped over a short time period at 0, 20, and 40 minutes past the hour was measured.

Because the oil in the line could not be warmed and night temperatures were low, pumping was continued, sometimes at a reduced rate, throughout the night. Test measurements were restricted to oil temperatures by thermometers and by temperature traverse, pressures by transducers, and flow rates by flowmeter.

2. *Laboratory tests*

The yield value of the oil was measured at 32° F. Tests were made:

(*a*) in glass U-tubes which had been filled with oil and immersed in the oil in the tank for some months;

(*b*) on samples which were taken from the tank into metal U-tubes immediately before testing.

Measurements of the " as received " pour point of the oil were also made. (The pour point by the IP Method [6] but without the 115° F thermal pre-treatment prior to cooling and testing.)

Viscosity measurements were made on both tank and pipeline samples. The sampling procedures ensured that no change in temperature occurred between sampling and testing. Every oil pumped was tested during the actual pumping trials. The shearing stress or rate of shear used in the viscometer measurements was normally that found in the actual pipeline under steady conditions.

Oils Used

Eight oils of widely differing type and crude source were pumped during the trials (see Table II). Oils A and E had high viscosities at 122° F and low pour points, while oils B and C had low viscosities and higher pour points. The oldest oil had been in Admiralty storage for about 20 years, while the youngest had been in storage for only just over one year. By pumping this wide variety of oils it was hoped to investigate as many factors as possible which might affect the pumpability of an oil in storage.

Results

1. *October trials*

After checking the operation of the instruments, a trial was made with oil A (which was almost Newtonian at the pumping temperature of 52·5° F with a viscosity, by co-axial cylinder viscometer, of 5·8 to 7·0 poise). Table III shows that the calculated viscosities in different sections agreed well with each other and with the laboratory viscosity measurements, except for the sections between the tank and point (*c*) (which included the swing arm) and the section (*h*–*i*). When large amounts of air were bled off from point (*h*) during the period when flow was throttled at the pump, the viscosity over the section (*h*–*i*) fell from 19 poise to 6·6 poise, but rose again to 20 to 30 poise

TABLE II

Data on Oils used in Steady State Trials

Reference letter	Crude source	Date received by Admiralty	Date received at depot	Inspection data						Pumping temperature in trials, ° F
				Specific gravity 60° F/60° F	Viscosity Redwood 1 at 122° F, sec	Wax content (methylene chloride), % wt	Asphaltenes, % wt	Pour point (IP Upper), ° F	Flow point (Method VII), ° F	
A (1)	Caribbean	Sep 1951	Apr 1952	0·933	195	6·1	4·1	20	0	36
B (37)	Persian Gulf	Mar 1951	Apr 1951	0·918	109	9·1	1·9	45	50	51
C (30)	Gulf, U.S.A.	1933	Nov 1952	0·910	100	7·2	0·7	50	40	47
D (36)	Persian Gulf	July 1954	July 1954	0·931	162	9·7	1·0	40	45	43
E (12)	Venezuela	Aug 1948	July 1952	0·928	245	9·4	1·5	25	10	48
F (40)	Persian Gulf	{Mar 1948} {Mar 1950}	Mar 1950	0·926	165	11·5	1·2	70	70	52
G (19)	,, ,,	Mar 1954	Mar 1954	0·934	161	—	—	—	30	49
H (31)	,, ,,	Mar 1954	Mar 1954	0·929	171	—	—	—	40	49

Numbers in brackets denote coding of reference (8) and are those in column 1.

TABLE III

Viscosity in Pipe (Poise) during Pumping of Oil A at 52·6° F in Calibration Trials (Oil Viscosity by Co-Axial Cylinder Viscometer: 5·8–7·0 Poise)

Pumping conditions Rate of shear in pipe, sec.$^{-1}$	Full suction 9·4	Throttled at pump 2·7	Throttled at tank 4·5
Section of line			
Tank–*c*	16·5–17·2	15·1–16·6	—
c–*d*	6·8– 7·5	6·7– 7·5	4·7– 5·7
d–*e*	6·3– 6·5	5·9– 7·1	5·3– 5·8
e–*f*	6·7– 7·0	8·0– 8·3	6·9– 7·0
f–*g*	7·0– 7·3	5·1– 7·3	5·3– 6·1
g–*h*	6·6– 7·6	6·5– 7·0	4·2– 4·8
h–*i*	19·5–21·9	18·8 → 6·6 *	25·5–28·2
i–*k*	6·2– 6·5	4·8– 5·7	5·4– 6·6

* → = decrease with time.

when the vacuum was increased by throttling at the tank. This effect is consistent with presence of air in the line, since increasing the vacuum would increase the volume of any air pockets present. Such air pockets would restrict the cross-section available to the oil and so increase the pipe viscosity.

2. Main February trials

(a) *Effect of air in the line.* In spite of the precautions to eliminate air, large quantities of air were bled off at the end of every run from the higher points of the line, and in consequence higher pipe viscosities were found in these sections (*c–d*, *d–e*, *h–i*). Table IV shows the magnitude of the effect with oils B and C.

TABLE IV
Effect of Air on Measured Pipe Viscosity

Section of line	Pipe viscosity, poise		Notes
	Oil B	Oil C	
a–b	—	34	
b–c	41	26	
c–d	60	40	Air in section
d–e	48	39	,, ,,
e–f	32	24	
f–g	33	24	
g–h	34	29	
h–i	45	53	,, ,,
i–j	28	24	
j–k	23	32	

Only part of the air in the line was bled off each time it was vented. How such large quantities of air entered the line is difficult to visualize. There was no evidence of any leaks into the line. Also laboratory experiments indicated that no significant amount of air was released from the oil at the lowest pressures found in the tests.

(b) *Oil temperatures in tanks.* Table II shows that although the oils were stored in the same depot in the same sized tanks, the pumping temperatures varied between 36° and 52° F. Oil A, a very fluid oil, had cooled to the ambient temperature (which had been about 36° F for the previous three weeks) while oils B and F, which had high flow points, had not cooled below 50° F. An examination of the tanks showed that with these oils the main bulk was effectively insulated by a thick crust of gelled oil which had formed on the tank walls. With oil F the gelled crust was so strong that it would support a brick. With oil E a layer of very viscous oil had the same insulating effect. It would therefore appear that although the high flow point oils are less pumpable at low temperatures, the bulk of such oils remains warmer.

(c) *Temperature variations.* In almost every run the temperature traverses showed that the outer layers of oil were cooler. The maximum oil temperatures were normally about midway between the centre of the pipe and the top. This distribution, previously found by Gill and Russell,[4] is due to the denser, cooler oil tending to accumulate on the bottom of the pipe. Rough heat transfer calculations indicated a considerable drop in temperature from the thermocouple next to the pipe wall. The measured difference between maximum and minimum oil temperatures varied between 1° and 12° F, but was normally about 6° F. This cooling of the outer layers of oil gives higher pipe viscosities than would be obtained if all the oil were at the warm central core temperature. An approximate method of calculation (described in Appendix 2) has therefore been developed to allow for temperature variations. Table V, which gives pipe viscosities measured on all oils in sections considered free from air, indicates the magnitude of the corrections necessary.

The oil, in addition to varying in temperature across the pipe, cooled as it flowed along the suction line. The cooling found, between 0·5° and 4° F, agreed with the values expected from heat transfer considerations. This cooling should increase viscosity as the oil travelled down the line, but breakdown in viscosity with time of shearing could have masked the effect.

(d) *Breakdown of viscosity on the full scale.* Since air increased the pipe viscosity in some of the later sections of the pipe, it was difficult to isolate breakdown of viscosity along the line. In some runs the viscosity in the earlier sections appeared to be higher

TABLE V
Pipe Viscosities Obtained in Large-Scale Trials

Oil	Pumping temperatures, ° F		Rate of shear, sec^{-1}	Average pipe viscosity (poise) uncorrected for non-isothermal distribution across pipe				Average pipe viscosity (poise) corrected for temperature distribution			
	Warm core (input oil temperature)	Pipe-wall (from temperature traverse)		Section *f–g*	Section *g–h*	Section *i–j*	Section *j–k*	Section *f–g*	Section *g–h*	Section *i–j*	Section *j–k*
A	36	33·5	2·2	26	27	29	22	24	25	27	20
B	50	41	2·2	33	35	28	24	17	18	14	12
C	45	37	2·2	17	22	20	18	11	14	13	12
D	43	36	1·0	66	76	78	67	44	50	52	44
E	46	42·5	2·2	—	—	69	75	—	—	55	60
G	44	43	6·5	—	24	21	22	—	22	20	21
H	49	46	8·6	16	20	17	8·5	—	—	—	—

than in the later sections. This is illustrated by oil B (Table IV), where, omitting the sections which have high viscosities because of air, the viscosity dropped along the line from 40–50 poise to 20–30 poise. As far as could be seen, any breakdown of viscosity occurred in the first few hundred feet of line.

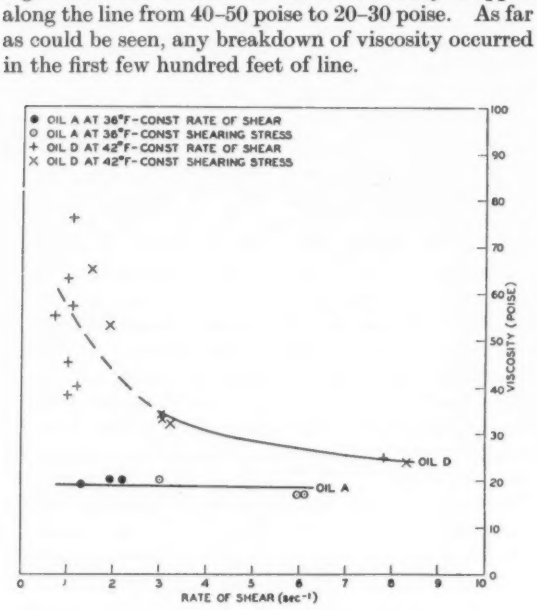
● OIL A AT 36°F-CONST RATE OF SHEAR
○ OIL A AT 36°F-CONST SHEARING STRESS
+ OIL D AT 42°F-CONST RATE OF SHEAR
× OIL D AT 42°F-CONST SHEARING STRESS
OIL D
OIL A
VISCOSITY (POISE)
RATE OF SHEAR (sec⁻¹)

FIG 4

VARIATION OF VISCOSITY WHEN BREAKDOWN IS COMPLETE
Oil A and Oil D

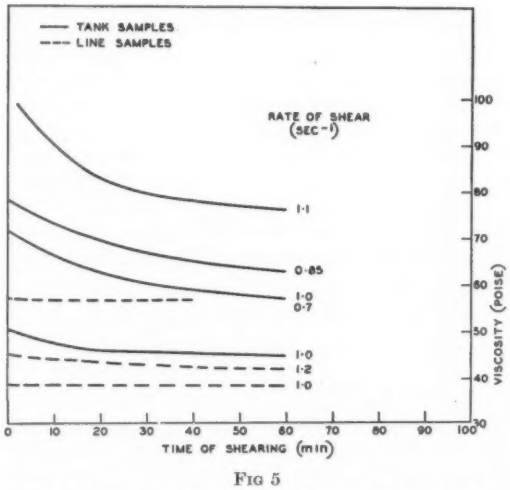

FIG 5

BREAKDOWN OF VISCOSITY WITH TIME OF SHEARING (OIL D) AT 42° F

(e) *Laboratory tests.* These measurements showed that the viscosities of the different oils were affected to different extents by time of shearing and change in rate of shear. Fig 4 shows that oil A was only slightly affected, while the most variable oil (oil D) was strongly affected. In addition, its viscosity at low rates of shear varied from sample to sample. Fig 5 shows that samples of oil D from the tank decreased in viscosity on shearing, while samples from the line did not, indicating that pumping through the line had probably caused viscosity breakdown. The tank samples appeared to be slightly more viscous than the line samples.

Comparison of Laboratory and Full-scale Results

Table VI shows that there was excellent agreement between laboratory viscosities at the pipeline rate of shear and the pipe viscosities. The laboratory viscosities were averages obtained by plotting all results when breakdown was complete on a rate of shear/shearing stress graph. The pipe viscosities were the averages for sections known to be free of air after correction for variation of temperature across the pipe. However, little correlation was obtained between laboratory yield values at 32° F and pumping trial results.

TABLE VI

Comparison of Viscosities from Full-Scale and Laboratory Tests

Oil	Test temperature, ° F	Viscosity (poise) from	
		Full-scale tests	Laboratory measurement
A	36	20	21
B	50	15	18
C	43	13	13
D	42	47	58
E	47	58	67
G	44	21	19
H	46	15	13

TABLE VII

Effect of Transfer on Viscosity of Admiralty Fuel Oil

Oil	A	B	C	D	E
Rate of shear	2	2	2·2	1	2·2
Pretreatment received	Equilibrium viscosity (poise)				
Tested on site	19·5	18	12	64	58
Tested after "isothermal" transfer to test laboratory	14·6	20	8·3	64	60
Tested after heating to 66° F for 3 days and cooling to test temperature at 1° F/min	12·0	2·7	11	21·5	19·5
Test temperature, ° F	35	50	44·5	42	45

At the end of the trials a programme was carried out to find the causes of the poor reproducibility of tests on samples transferred to co-operating laboratories. Samples of oils A, B, C, D, and E were taken from the centre–centre of the tanks. Part of each sample was tested in the viscometer on site. The other part was tested at the laboratory after transfer in a Thermos flask packed into an insulated haybox which prevented the sample temperature from changing by more than 1°–2° F. After repeating the "on site" test, the re-

maining part of the sample was then held for three days at 66° F, to reproduce the temperatures to which an ordinary sample might be subjected. It was then re-cooled to the pumping temperature at 1° F/min and re-tested. Table VII shows that the isothermally transferred samples gave effectively the "on-site" viscosity but the heated samples did not.

II. START-UP OF A GELLED LINE

Depot operations prevented work on gelled lines in the trials described in Section I. Work was required to study how a gelled oil could be made to move in a pipeline and how quickly the maximum flow rate could be obtained once the oil had yielded. Pumping tests were therefore made at a depot where oil could be pumped into a test line in the summer and allowed to remain quiescent in the line throughout the winter, thus building up the maximum amount of gel structure. To obtain the maximum information, the oil used had to have a yield value at the testing temperatures such that start-up was difficult but not impossible. Filling the test line in October 1955 with an oil similar to the oil F showed it to be much too viscous, even at summer temperatures. Oil J (flow point 55° F, compared with 70° F for oil F) was therefore chosen. Other inspection data are given in Table VIII.

TABLE VIII

Inspection Data on Oil J Pumped in Start-Up Trials

Test	Results
Specific gravity at 60° F/60° F	0·926
Pour point (IP Upper), ° F	55
Flow point (Method VII), ° F	55
Viscosity at 122° F Redwood 1, sec	166
Asphaltenes, % wt	2·44
Wax content (methylene chloride), % wt	11·1
Sulphur, % wt	3·04

Oil J is coded as oil 41 in reference (8).

Fig 6 is a diagram of the pumping circuit used in the trials and shows survey heights. The cross-line between valves D and C could be closed off throughout the winter and contained tank 1, in which to store the test oil. Instrumentation was arranged in the expectation that oil would be pumped from tank 1 via valves B and C through the ring main to the pump. If, however, this test section was too long to start up, an attempt could be made to pump the section between tank 1 and valve D. Except for the 12-inch branch from the cross-line to tank 1, the line consisted entirely of nominal 14-inch diameter pipe. The pump used was a Duplex double-acting steam pump with a nominal capacity of 200 tons/hour. The maximum delivery pressure was 100 psig and the nominal suction was 20 inches Hg, although in practice 25 inches Hg was obtained. The pump had a suction surge reservoir with a capacity of 1800 gallons.

Instrumentation

1. *Pipeline instruments*

Only minor modifications, detailed below, were required to the instrumentation used successfully in the steady-state trials.

(*a*) *Line pressures.* Line pressures were again measured by transducers, mercury manometers, and Bourdon gauges. In addition, four differential water manometers were fitted to the line 25 feet apart in the side leg to tank 1 to investigate structure breakdown.

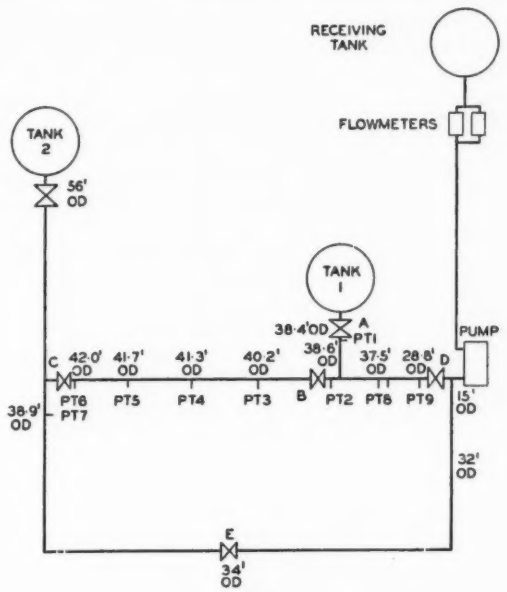

FIG 6

LAYOUT OF TEST LINE SHOWING HEIGHTS ABOVE ORDNANCE DATUM

(*b*) *Oil temperatures.* These were measured by mercury-in-glass thermometers and by four thermocouple traverse units. These could be fitted when the pipeline was under pressure or vacuum. The cross-line was fitted with tapping points for vertical traverses at points 1 to 6 and a horizontal traverse at point 1. The traverse at point 5 was connected to a Honeywell–Brown recorder to give a complete record throughout the trials. This recorder also measured pipewall top and bottom temperatures at point 5. Temperature surveys were made of tanks 1 and 2 with an iron–constantan thermocouple fitted on to a 15-lb pointed brass weight (to penetrate any oil gel present). To avoid temperature effects due to the weight, the thermocouple junction was arranged 3 inches out from the side of the weight.

(*c*) *Flow rates.* The instruments provided were:

(i) Two positive displacement flowmeters fitted in parallel near the delivery tank. They had ranges of 0 to 25 gal/min and 0 to 250 gal/min.

(ii) A small propeller type oil velocity probe,[7] which could be fitted into the pipe through $\frac{3}{4}$-inch cocks, was used in an attempt to measure the velocity distribution across the pipe.

(*d*) *Ancillary measurements.* The ground, solar, and shade temperatures were shown on the Honeywell–Brown recorder.

2. *Laboratory instruments*

In addition to the three viscometers used previously, a special viscometer was designed by the Fuel Research Station to avoid errors caused by sampling by measuring the viscosity of the oil in the tank. The

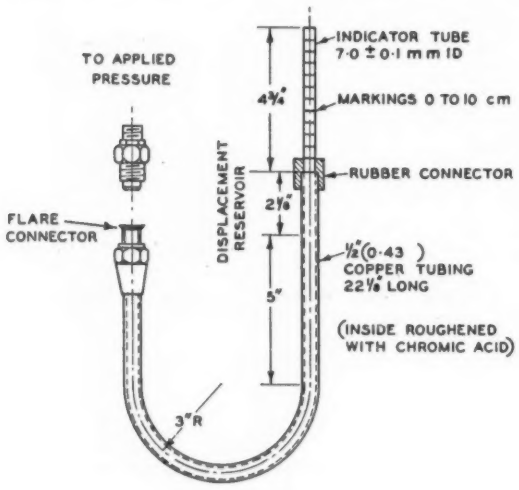

FIG 7

CALIFORNIA RESEARCH CORPORATION U-TUBE AND FLOW INDICATOR TUBE

viscometer (which was shown at the 1956 Physical Society Exhibition) operated by rotating a single cylinder at constant torque in a volume of oil which is sufficiently large to be considered infinite.

Since these trials were to study the start-up of a gelled pipeline, yield value measurements on undisturbed oil were considered essential. These were measured in three ways:

(*a*) *In yield value* U*-tubes developed by AFLAC Panel F.*[1] These were filled when the line was filled, packed around with insulation, and left by the pipeline, so that they would undergo similar temperature changes to the oil in the pipeline.

(*b*) *In California Research Corporation* U*-tubes* (see Fig 7). These were filled and stored as above and then used both to measure yield value and initial viscosity.

(*c*) On the surface of the oil by a set of 45° half apex angle penetrometer cones of different sizes and weights.

Procedure

1. *Filling the test line* (*October 1955*)

Four line capacities of oil J were pumped from tank 2 through the ring main and cross-line to clear the previous oil. 3000 tons of oil were then transferred from tank 2 to tank 1 for the main pumping trials. Measurements during filling showed the oil had a viscosity of about 10 poise at 55° F and also that the line was free from obstructions. After filling tank 1 and the test line, valves C and D were locked shut. Valves A and B were, however, locked open to allow oil from tank 1 to flow into the line when the oil contracted during cooling. Bourdon gauges and thermometers were left in position so that the pressure and temperature changes could be observed throughout the winter by depot staff.

2. *Start-up trials* (*February 1956*)

(*a*) *Laboratory measurements.* Laboratory viscosity measurements were made on samples from the tanks, from the line, and from the barrels which had been stored by the pipeline throughout the winter. In addition, temperature and viscosity surveys (using the immersion viscometer) were made of tanks 1 and 2 and penetrometer measurements made on the surface of the oil in the tanks and in the barrels. The yield values of

TABLE IX

Data Obtained during "Backing-Up" Periods

Run number	Selection of line from pump containing non-gelled oil	Conditions when recorded flow rate was a minimum					
		Time to reach minimum flow rate, min	Minimum flow rate by flowmeter, gal/min	Gallons of oil pumped to minimum flow rate	Pressure (psig) at		
					Pump	Point 7	Tank 2
1	Pump—point E	70	0	2800	−12	—	+4·5
2	Pump—point C—Tank 2 valve	75	5	3650	− 9	−9·4	—
3	Pump—point C—{Tank 1 / Tank 2 valve}	60	15–20	2300	−11	−2·9	—
7	Pump—Tank 2	60	0	5480	−10	−8	−8·5
11	Pump—Tank 2	60	0	3256	−11	—	—
12	Pump—Tank 2	60	0	2760	−11	—	—

the oils stored in the test U-tubes and the California Research tubes were also measured.

(*b*) *Trials measurements.* The pressure, temperature, and flow rates were taken sufficiently frequently to follow any changes. The velocity probe readings were recorded and also a continuous record of the temperature distribution across the pipe was taken on the Honeywell–Brown recorder. The tests were continued until steady rates of flow were obtained.

Very high rates of flow were recorded on the flowmeter immediately after starting the pumps. This flow rate always decreased with time and fell to zero in one or two tests. The phenomenon (called " backing up " by the depot staff) was investigated further by pumping from a line having all inlet oil valves closed. Table IX summarizes the data recorded. It was found that:

(i) The backing-up period lasted for about one hour and flow fell to zero if all inlet oil valves were shut. Therefore the recorded flows were not due to leaking valves.

(ii) On starting the pump the flow rate was about 300 gal/min.

(iii) The longer the length of line from the pump containing non-gelled oil, the greater tended to be the volume of oil pumped in the backing-up period.

(iv) The gauge pressures at the end of a backing-up run equalized at −9 psig.

Since tank 2 was 35 feet above the pump, equal gauge readings could be obtained only if the line were partly full of air. On the assumption that air was present, the following mechanism for " backing-up " was suggested:

(1) Air in the 1800-gallon surge reservoir on the pump suction expanded and gave an immediate flow of up to about 1200 gallons. The rate of flow of this oil would not be limited by viscosity.

(2) The vacuum so produced in the surge tank, together with the change in hydrostatic head of oil, caused the oil to cavitate at some point in the rapidly rising line from the pump. Oil was then pumped out of the line from the pump to point F. The gradient of the line would give a rapid flow even with a viscous oil. This stage could account for an additional 720 gallons.

(3) Expansion of air which was present in large quantities in the almost level ring main, and possibly also in side lines to tanks, then caused the viscous oil to flow slowly over the " waterfall " at point F. It was estimated that the volume of oil which flowed to the pump could be up to about half of the volume of air present in the line. In the later stages the air in the rising section of line would join the air in the flat section, giving a continuous layer of air from the pump to tank 2, thus equalizing pressures along the line.

The delivery flowmeter therefore recorded the oil flow from the storage tank only under steady conditions. Indirect measurements of flow rates in the test section could, however, be made by using the flowmeter results in conjunction with the velocity probe and the variation of the oil temperature along the pipeline with time.

When gelled oil was present in the line the temperature traverse at point 5 showed that the oil temperature across the whole of the pipe rose from 38° to 50° F (the tank temperature) in less than 5 minutes. Thus the gelled oil moved as a plug, and the movement of the temperature interface along the pipe gave the flow rates. When the oil was not gelled the velocity meter showed a steady increase in velocity until the warm oil from the tank reached it. The meter is known to be sensitive to oil viscosity,[7] and the indicated flow fell to about half at this point. However, the oil viscosity at the flowmeter remained roughly constant thereafter, and it was possible to calibrate the velocity meter against the positive displacement meter when steady conditions had been reached. The calibration constant for the earlier part of the test was obtained by assuming that the flow rate was the same immediately before and immediately after the warm oil reached the probe.

Tests Made

1. *Start-up of oil at 38° F after storage in line for four months*

The pressure head in the tank was transmitted down the line until mid-December, when the temperature fell abruptly to 33° F. Vacuum was then recorded at several points, showing that the yield value of the oil was sufficient (100 dynes/cm² or more) to prevent the oil from moving along the line to take up contraction on cooling.

Once the initial " backing-up " was complete, the flowmeter indicated zero flow rate for a short time in the start-up test. During this period the pressure at the end of the gelled test section fell slowly to the pump pressure. The pressures at the other points also fell and gave a linear pressure drop over the gelled section. The pressure at point 5 then suddenly fell, reducing the pressure differential over sections 5–6 and increasing it over the other sections (see Fig 8). The line pressure then began to rise slowly and the flowmeter flow rates to increase. This behaviour shows that the gel structure of the oil in sections 5–6 suddenly broke down, thus causing the pressure drop over this section to fall to zero. The total available pressure then acted on the rest of the line and increased the shearing stress to the yield value of the oil, which is shown by Fig 8 to be about 400 dynes/cm². Flow throughout the test section then commenced.

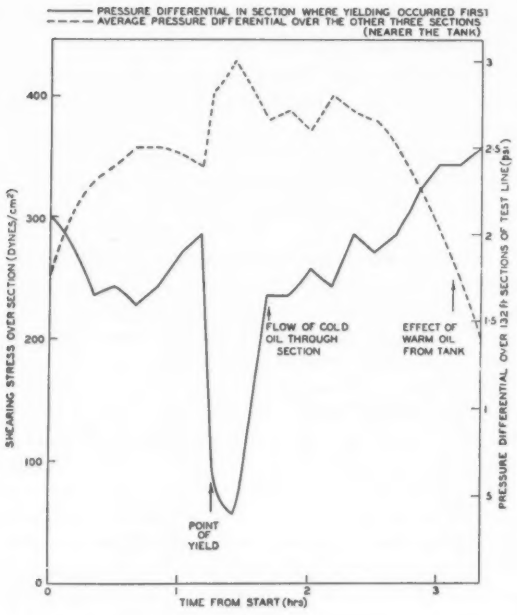
PRESSURE DIFFERENTIAL IN SECTION WHERE YIELDING OCCURRED FIRST
AVERAGE PRESSURE DIFFERENTIAL OVER THE OTHER THREE SECTIONS (NEARER THE TANK)
SHEARING STRESS OVER SECTION (DYNES/cm²)
PRESSURE DIFFERENTIAL OVER 132 ft SECTIONS OF TEST LINE (psi)
FLOW OF COLD OIL THROUGH SECTION
EFFECT OF WARM OIL FROM TANK
POINT OF YIELD
TIME FROM START (hrs)

FIG 8

BREAKDOWN OF GELLED OIL IN PIPELINE PRESSURE DIFFERENTIAL OVER 132-FT SECTIONS OF 14-INCH DIA TEST LINE

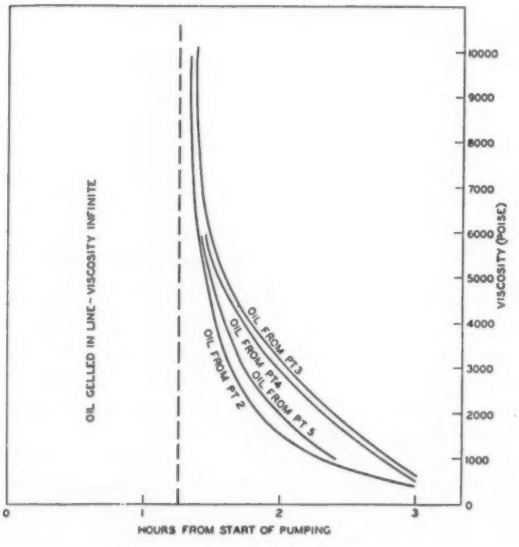
OIL GELLED IN LINE - VISCOSITY INFINITE
OIL FROM PT 3
OIL FROM PT 4
OIL FROM PT 5
OIL FROM PT 2
VISCOSITY (POISE)
HOURS FROM START OF PUMPING

FIG 9

VISCOSITY BREAKDOWN OF OIL DURING START-UP

Shearing stress approx 350 dynes/cm²

Over the next 90 minutes the shearing stress acting on the oil in the test line remained relatively constant. This, together with the estimated flow rate, gave the viscosity/time of shearing curves shown in Fig 9. These show that when the oil yielded it first moved slowly down the line with a viscosity of about 10,000 poise, but by the time the oil from the first section left the pipe its viscosity had fallen to about 400 poise. The warmer tank oil had a pipe viscosity at the exit from the tank of about 600–1000 poise at 50° F, which fell to 100 poise over the 500-feet test section.

2. *Start-up at 43° F of oil which had cooled from 50° F during two days storage in the line*

The velocity probe, which was in the centre of the line at point 6, showed that the oil moved immediately suction was applied. This oil therefore had zero yield value at 43° F. The flow rate then increased steadily with time. The Honeywell–Brown recorder at point 5 showed that in this run the oil did not move as a plug, since it took over 2 hours for the oil at 1 inch from the bottom of the pipe to reach the temperature of the central core. The average oil velocity was half the velocity of the central core of warmer oil entering from the tank. This suggests a parabolic velocity distribution across the pipe.

The pipe viscosities of the oil in sections 2–6 decreased from more than 1000 poise to approximately 350 poise as the oil was sheared. Due to the lagging on the tank leg, the oil in it was warmer than in the test line. This warmer oil has a viscosity initially of 300 poise, falling to about 150 poise 2 hours later. At the end of the run, after 9 hours pumping, the viscosity of the oil coming from the tank was 100 poise at the beginning of the line, falling to 70 poise at the end.

3. *Steady state periods*

The start-up trials were continued until steady conditions had been reached, so that the pressure differentials along the pipeline could be used to find out if the viscosity of a fuel oil decreases as it is pumped along a pipeline in the same way as it does when sheared in a laboratory viscometer. In addition,

TABLE X

Yield Values Measured in Laboratory Instruments

Method	Sample point	Temperature, ° F	Yield value, dynes/cm²
Penetrometer .	Drum at Pt 3	37	2500–3700
	Drum at Pt 2	36	2000–3000
	Tank 2	38	2900–4400
	Tank 1	40	2700–4200
U-tube . .	—	36	780
	—	36	570
	—	32	930
Cal. Research Tube . .	—	36	*ca.* 350

Note 1: Penetrometer yield value calculated from formula

$$\text{Yield value} = \frac{(\text{apparent weight of cone in gel})}{5\pi[\text{penetration}]^2}\ \text{g.}$$

Note 2: Full-scale yield value = 400 dynes/cm² at 38° F.

further runs were made after the cold oil had been cleared from the line to obtain full-scale data on the effect of shearing stress on the measured pipe viscosity. The shearing stress at the pipe wall was lowered by

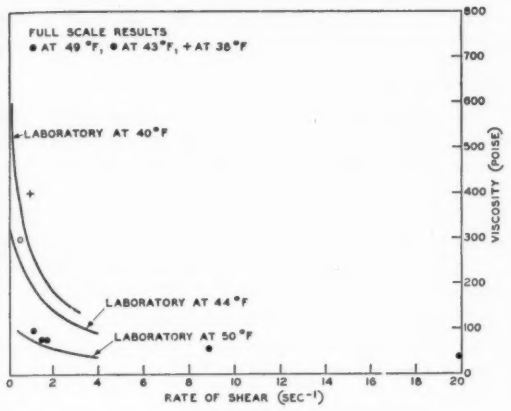
FULL SCALE RESULTS
● AT 49 °F, ● AT 43 °F, + AT 38 °F
LABORATORY AT 40 °F
LABORATORY AT 44 °F
LABORATORY AT 50 °F
VISCOSITY (POISE)
RATE OF SHEAR (SEC⁻¹)

FIG 10

FULL-SCALE AND LABORATORY VISCOSITIES WHEN BREAKDOWN OF VISCOSITY COMPLETE

controlling the pump suction pressure. The results, shown in Fig 10, show the marked effect of rate of shear, and hence shearing stress, on the measured pipe viscosity. At 49° F an increase in shearing stress from 100 to 800 dynes/cm² caused a decrease in pipe viscosity from 100 to 40 poise. At 44°–45° F the combination of 4° F drop in temperature and a very low rate of shear increased this viscosity to 350–500 poise.

The breakdown of an oil as it travels down the pipe was clearly shown in the two start-up runs, where both the hot and cold oil showed a clearly marked decrease in viscosity as the oil travelled down the line. The pipe viscosities obtained from both transducer and water gauge data in the steady state runs (oil at 49° F) also show that breakdown took place, but indicate that it was complete by the end of the first two sections.

Laboratory Tests and their Relation to Full-Scale Results

1. *Yield values*

The results of testing oil that had undergone the same temperatures as the gelled oil in the test line are given in Table X. It is evident that the cone penetrometer method gives a far higher yield value than found in the start-up tests. The penetrometer method does not therefore indicate the effective resistance of a gelled oil to start-up. The other two methods (U-tube and California Research U-tube) gave values which were quite close to the full-scale yield value of 400 dynes/cm². Since the full-scale trial was at a temperature of 38° F, 2° F above the temperatures of the laboratory tests, the U-tube method, which gave results somewhat above that found in practice, probably agrees more closely with the full-scale than does the California Research method. The U-tube method is also to be preferred on the grounds of simplicity.

2. *Viscosities*

Start-up of lines. It was hoped that measurements made with the immersion viscometer would satisfactorily predict the start-up behaviour, since this viscometer reduced sample handling to a minimum. The viscosities so measured were all much higher than found in the tests, and this was attributed to the rapid fall-off of shearing stress round the viscometer. Because of this, the instrument does not appear suitable to evaluate highly non-Newtonian materials.

The measurements on the California Research U-tubes were evaluated to give viscosity once yielding had occurred. Extremely high viscosities were obtained (about 1,000,000 poise at 36° F, falling to 16,000 poise at 50° F). These figures show that the instrument does not correlate with practice, where the highest viscosity, obtained immediately after yielding at 38° F, was about 10,000 poise.

The tests made in co-axial cylinder viscometers showed that the viscosity of the test oil was very sensitive to the conditions of test. Doubling the shear-

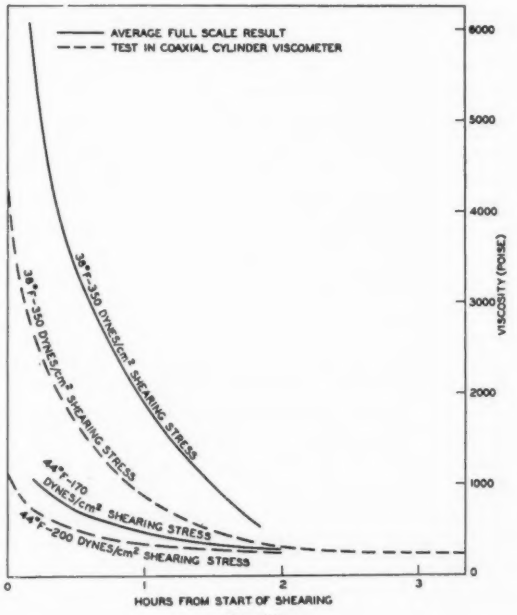
AVERAGE FULL SCALE RESULT
TEST IN COAXIAL CYLINDER VISCOMETER
38°F-350 DYNES/cm² SHEARING STRESS
38°F-350 DYNES/cm² SHEARING STRESS
44°F-170 DYNES/cm² SHEARING STRESS
44°F-200 DYNES/cm² SHEARING STRESS
VISCOSITY (POISE)
HOURS FROM START OF SHEARING

FIG 11

COMPARISON OF BREAKDOWN OF VISCOSITY ON THE FULL SCALE WITH THAT FOUND IN VISCOMETER

ing stress caused viscosities measured soon after commencing shearing to vary by up to 10 to 20 times. The viscosities obtained when all possible breakdown had taken place were less affected (see Fig 10), and

the results from constant shearing stress and constant rate of shearing instruments agreed quite well with each other. Similar good agreement is shown in Fig 11 for the breakdown period by plotting the viscosities which were measured under conditions closely approximating the full-scale conditions at 38° F and 44° F, together with the viscosity/time of shearing curves found on the full scale.

These results confirm that the co-axial cylinder viscometer satisfactorily determines the flow properties of fuel oils down to temperatures somewhat below their pour points.

III. TESTS ON OILS STORED IN UNDERGROUND INSTALLATIONS

Temperature fluctuations have long been thought to be the cause of the increase in viscosity that can occur when a waxy fuel ages. It was therefore thought that fuel oils in underground installations, where the temperature is practically constant, would probably have better flow properties than similar oils stored in surface tanks. A series of trials were therefore made to find out if this were so.

In the U.K. the average ground temperatures several feet below the surface lie between 48° and 54° F, and oils in underground installations are therefore normally at these temperatures. Problems are not generally encountered in the suction lines, but the delivery lines, which are normally buried, can be long and might present a serious flow restriction with high viscosity oil. Pumps are in general available, so that when making trials relatively high pressure drops can be measured. Also it is usual to pump fairly large parcels of oil.

Instrumentation

1. *Flow rate*

The pumping trials with each oil extended over at least one day, and steady conditions were maintained through most of this time. It was therefore sufficient to estimate the average flow rates by taking dips on the delivery tanks. This was normally done once an hour.

2. *Pressures*

Measurements were primarily made on the delivery side of the pump, where both the absolute pressures and pressure differentials were high. It was therefore sufficient to measure pressures with Bourdon gauges.

3. *Temperatures*

The installations were effectively insulated, and therefore the oil temperature had become practically constant throughout the storage tank. Also the pipelines were buried and the temperature of the soil surrounding them was about the same temperature as the oil in the tanks. The oil temperature could therefore be found accurately by measuring the temperatures of samples taken in Thermos flasks. In addition, exposed thermometers in the line were used.

The full-scale instrumentation was therefore much simpler than in the previous tests.

4. *Laboratory instruments*

The flow points of all the oils pumped (see Table XI) were below the pumping temperature. The laboratory tests were therefore restricted to measurement of viscosity. The trials marked the first introduction of the Ferranti Portable Viscometer (Model VH fitted with VM cylinders and 20 g cm spring). This type of Ferranti viscometer appeared to be capable of covering the range of shearing stresses and rates of shear normally encountered in the pumping of Admiralty fuel oil. Its important dimension differed from those of the viscometers previously used (see Table I). In addition, the constant shearing stress viscometer used previously was employed.

TABLE XI

Inspection Data on Oils Pumped from Underground Depots

Oil reference	Crude source	Storage time		Inspection data					
		Year	Month	Specific gravity 60° F/60° F	Viscosity Redwood 1 at 122° F, sec	Wax (methylene (chloride), % wt	Asphaltenes, % wt	Sulphur, % wt	Flow point (Method VII), ° F
K	Middle East	—	8	0·929	166	6·9	1·54	3·00	30
L	Middle East	1	2	0·932	165	—	—	2·72	30
M	Middle East	5	—	0·920	117	6·8	2·31	1·48	45
N	Trinidad	1	2	0·937	196	—	—	1·46	<0
O	Middle East	2	3	0·934	162	—	—	3·04	30

Oils Pumped

Only a relatively restricted range of oils was available. Of the oils pumped, Table XI shows that three oils, K, L, and O, were very similar. Oil N was pumped because a preliminary investigation by viscometer had shown it to have a surface layer of high viscosity.

Full-Scale Tests

At least 2 hours were allowed for conditions to stabilize after any change in conditions had been made.

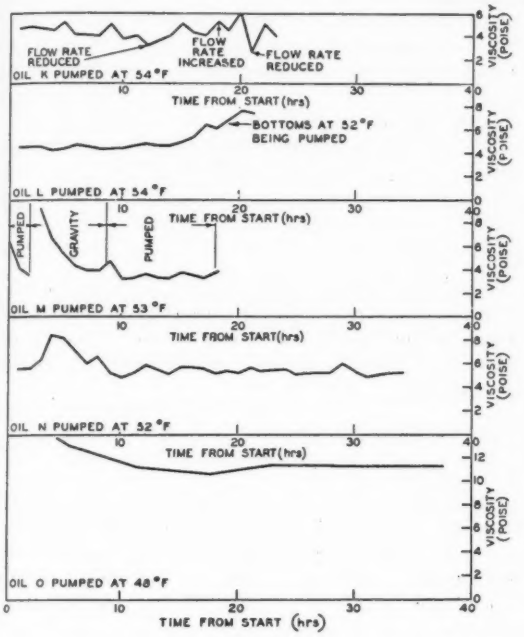

FIG 12

PIPE VISCOSITIES DURING PUMPING OF OIL FROM UNDERGROUND STORAGE

The time to stabilize is indicated by Fig 12, which shows that changes in conditions with oil K required at least one hour to steady out. With oil M, changing over from pumping to gravity flow caused an apparent increase in viscosity for some time. The reason for this is not clear, but may be due to air pockets in the line, which were of negligible size under pumping conditions, expanding under gravity flow, obstructing the line, and taking some time to clear from the line.

In these tests the rates of shear were relatively high (between 10 and 20 seconds^{-1}), and changing the flow rate did not affect the line viscosity. The calculated viscosities were low (4–12 poise), but were noticeably temperature-dependent. A change of temperature from 54° to 48° F appears equivalent to an increase from 4 to 12 poise, and the pipe viscosity on oil L clearly showed the 2° F difference between the top and bottom of the tank.

Laboratory Tests and their Relation with Full Scale

It was found that the Ferranti and the constant shearing stress viscometers gave closely the same viscosities except with oil N. The latter difference could have been caused by the difficulties in sampling. Table XII shows that with this oil the viscometers detected a layer of viscous oil at the surface, the consistency of which varied rapidly with sampling depth. Laboratory tests showed this oil to be more waxy than the main bulk. Table XII also shows that samples from the line were less viscous than the tank samples. With the exception of the tank sample of oil M, the oils showed little, if any, evidence of non-Newtonian viscosity behaviour.

Table XIII shows that laboratory measurements on the line samples agreed better with the pipe viscosities than did measurements on the tank samples. This was particularly the case for oil N. Although this oil was completely pumped out, no evidence of the viscous surface layer detected by viscometer was found during pumping.

TABLE XII

Laboratory Viscosity Measurements on Samples Tested in the Ferranti Portable Viscometer without Change of Temperature

Oil	Sample point	Test temperature, ° F	Rate of shear, sec^{-1}			Notes
			1·625	6·75	18·75	
K	Tank	53	5·2	5·1–4·9	4·8–4·7	
L	Tank	54	5·9–4·2	5·7–4·7	5·2–4·2	
	Line	54	4·7–3·4	4·8–3·8	4·9–3·4	
M	Tank	53	14·6–8·8	9·4–6·3	6·5–4·8	
	Line	53	3·8–3·0	3·7–2·8	3·5–2·6	
N	Tank—2 ft from top	53	60	—	—	Samples contained 11% of wax and had flow points of 95° F
	—6 ft ,,	53	10·2	9·7	9·1	
	—12 ft ,,	53	9·6	9·3	8·0	Samples contained 5·5% of wax and had flow points of 10° F
	—bottom	53	8·3	7·5	—	
	—sample during pumping	53	6·2	6·2	6·1*	
	Line	53	5·6–4·0	5·3–5·2	5·1–5·1	
O	Tank—top	48	9·9	9·5	9·5	
	middle	48	13·9	12·5	11·5	
	bottom	48	19·5	16·5	—	
	Line	48	11·5–6·8	11·1–6·8	10·8–7·1	

* Results of various determinations gave same viscosity at 18·75 sec^{-1}

TABLE XIII

Comparison of Pipeline and Laboratory Viscosities on Oils from Underground Storage

Oil	Test temperature, ° F	Pipeline viscosity, poise	Viscosity in Ferranti viscometer (poise) of sample from		Notes
			Line	Tank	
K	54	*ca* 4	—	4·7	
L	54	4·4–4·8	4·9–3·4	5·2–4·2	
M	53	3·2–4·0	3·5–2·6	6·5–4·8	
N	52	5·0–6·0	5·1	6·0–8·0	Much higher viscosities measured on surface layer in tank
O	48	10·5–11·5	10·8–7·1	9–15	

The trials therefore confirmed that a co-axial cylinder viscometer gave a good assessment of the low temperature flow properties of Admiralty fuel oil. They also showed that the commercially available Ferranti viscometer was as suitable as the specially constructed research instruments used previously.

An unexpected result was that handling the oil through a pump reduced its viscosity noticeably. Thus viscometer measurements on tanks rated oils slightly adversely when compared with pumping trial results. It also appeared that small quantities of high viscosity oil in the tank would not show up during a pumping operation.

IV. SHIPS' PUMPING TRIALS

Fuel oil is normally heated before loading into ships' tanks. Once at sea, the oil is liable to be kept in motion by the pitching and rolling motion of the ship. Both these factors could cause the pumpability of fuel oils in ships to be different from shore storage. A series of winter Arctic cruises was therefore arranged so that the temperature conditions holding in ships could be determined and pumping trials made to determine fuel oil pumpability under these conditions.

TABLE XIV

Inspection Data on Fuels Pumped in Full-Scale Ships' Trials

	Oil P (destroyer trial)	Oil Q (tanker (trial)	Oil R (tanker trial)
Specific gravity 60° F/ 60° F	0·934	0·930	0·934
Flash point, ° F	202	193	—
Explosiveness, %	—	5	—
Redwood 1 viscosity at 122° F, sec	225	163	170
Flow point (Method VII), ° F	—	35	35
Pour point (IP Upper), ° F	40	—	—
Sediment, % wt	—	0·01	—
Sulphur, % wt	—	3·25	—
Ash, % wt	—	0·02	—
Wax content, % wt.	7·5	—	—

Oils Pumped

Table XIV shows that the oil pumped in the destroyer trials was of higher viscosity and pour point than the oils used in the tanker trials. These were typical of fuels meeting the present Admiralty specification.

Trials Instrumentation

1. *Temperatures*

The tanks holding the fuel oils to be assessed were fitted with a large number of thermocouple points so that the average oil temperature and temperature distributions could be found. In the earlier trials line temperatures were measured by thermometers strapped to the suction lines; in the later trials thermocouples were fitted into glands through the pipeline.

2. *Flow rates*

In the early trial these were measured by counting the strokes of the reciprocating fuel pump and checked by making tank dips. In the later trial it was only possible to use tank dips. To obtain the best accuracy, simultaneous measurements were taken on the delivery and receiving tanks. Since these were on opposite sides of the ship, the average flow rate from the delivery and receiving tank tended to eliminate errors due to the roll of the ship.

3. *Pressure measurements*

These were measured by Bourdon gauges. In all except one instance the line pressures were above atmospheric pressure. Probably because of this the pressure readings did not appear to indicate air in the line. The Bourdon gauge measurements had to be adjusted to allow for the trim of the ship, but since the ship was pitching somewhat during the trials, it was difficult to determine the correct trim.

Procedure

The oils used in the tanker trial were tested for viscosity before loading and at regular intervals through the cruise to establish correlation with pumping results. One tank of oil Q was heated to

find out if preheating the oil reduced its viscosity in the same way as found (see Table VII) during the steady state flow trials described in Section I. It was hoped to reach a minimum oil temperature of 36° F before pumping, and in order to achieve this empty fuel tanks were filled with water once the tanker was in Arctic waters. In spite of this, the lowest oil temperature reached was 41° F.

The pumping trials were made on the tanker and the destroyer when the oil had dropped to its minimum temperature. This was recorded at the time the ships were about to leave Arctic waters. In both trials the longest possible suction lines were used. In the destroyer this entailed using the line connecting the most isolated tank to the pump farthest from it; in the tanker a ring main, normally used for transferring oil from one tank to another, was used.

Results

1. *Fuel temperatures*

Fig 13 shows that the large tanks in the tanker cooled somewhat slower than the small fuel tanks of operational vessels. This was probably due to the smaller surface/volume ratio of the tanks in the tanker.

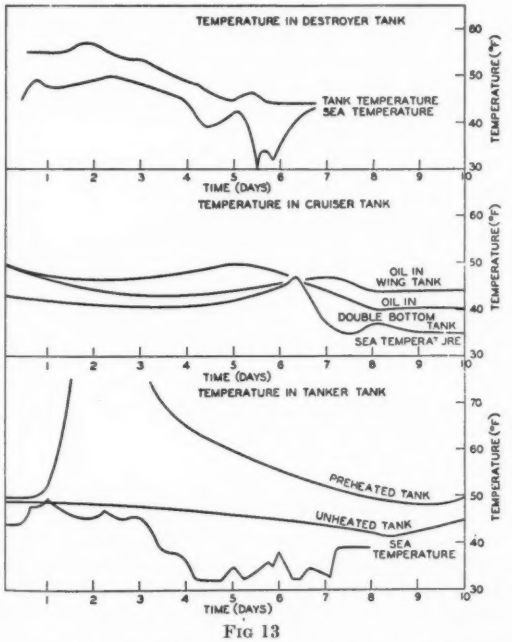

Fig 13

COOLING OF FUEL OIL IN UNHEATED TANKS IN ARCTIC WATERS

Once the fuel temperature approached 40° F, the rate of cooling appeared to decrease and no fuel tank temperatures below 40° F were ever recorded. It therefore appears that fuel temperatures of 40° F or below will only very rarely be encountered.

2. *Pumping results*

Both the oils were pumped at 44° F, and both were found to have viscosities of 12–14 poise (Table XV). No evidence of non-Newtonian behaviour was found in the trials. This relatively low viscosity could have

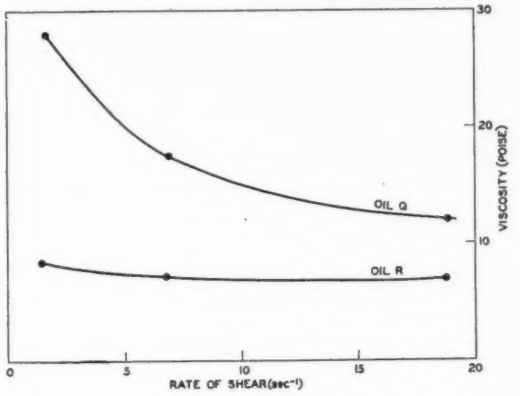

Fig 14

VISCOSITY *v.* RATE OF SHEAR FOR OILS Q AND R BEFORE PUMPING ON TO TANKER

Temperature 51° F

been due to the continuous agitation of the oils in the fuel tanks caused by the motion of the ship or to an improvement in pumpability due to shearing the oil on loading. The relatively short storage time at 44° F might also have contributed to the lowering of viscosity.

TABLE XV

Pumping Trials on Ships at 44° F

(*a*) *Destroyer Trials on Oil P*

Period of pumping, minutes	Rate of shear sec^{-1}	Viscosity, poise
30	14·7	14·6
45	17·6	12·3

(*b*) *Tanker Trials on Oil Q*

Time from start of pumping, min	Rate of shear, sec^{-1}	Viscosity, poise
10	9·5	13·3
30	9·5	11·6
50	9·5	9·8
70	24·0	12·7
90	24·0	11·7
110	24·0	10·6

Note.—Pumping rate increased at 60 minutes.

Relation of Pumping Trial Results to Viscometer Results

Viscosities were measured with the Ferranti viscometer on oils Q and R before loading on the tanker and throughout the period of the Arctic cruise. Tests on these oils from the storage reservoir (Fig 14) showed

that the viscosity of oil Q depended on the rate of shear used. After loading no evidence of non-Newtonian behaviour was found. Also the viscosity at 51° F had been reduced. Fig 15 shows that this latter effect was

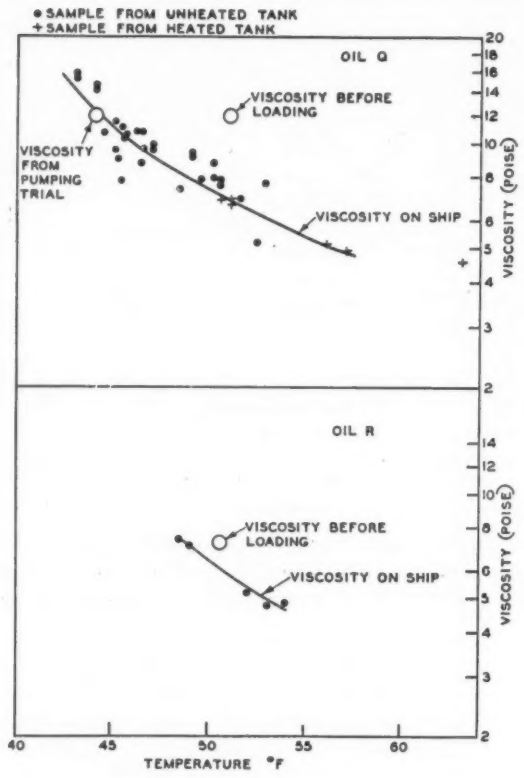

Fig 15

VISCOSITIES OF OILS USED IN TANKER TRIALS

very noticeable for the non-Newtonian oil Q and could still be detected with oil R. The Ferranti viscometer measurements showed no difference in viscosity between the heated and unheated tanks of oil Q. They also gave the same viscosity (12 poise) as deduced from the pumping trial measurements.

CONCLUSIONS FROM TRIAL SERIES

The series of trials described above showed that in order to be successful, careful planning and extensive instrumentation is required, especially when subatmospheric pressures are encountered. The requirements for adequate instrumentation were demonstrated by the first series of steady state trials (Section I) and also by an attempt to start-up the poorly instrumented line from tank 2 to the pump in the start-up trials (Section II). Neither of these trials could be used to characterize the oil being pumped because of the lack of detailed knowledge on pressure and flow rate.

The trials demonstrated that a suction pipeline could be restricted by air locks forming in the pipeline. This air could, in certain cases, halve the flow rates in a pipeline by causing high pressure drops over short sections of the line. As far as could be seen, delivery pipelines were unaffected by air pockets.

When the higher viscosity oils were being pumped, the flow rates were low and with oil F (Section I) a viscosity of about 200 poise reduced the flow rate to an unacceptably low value. Similarly, the high viscosities met with during the start-up trials (Section II) would only be acceptable during clearance of a line. The maximum viscosity that could be tolerated for continuous pumping is probably not more than 50 poise.

It was difficult to directly assess the effect of different storage conditions on the flow properties of fuel oils at temperatures in the range 40°–50° F. With the higher pour point oils B and M, surface storage appeared to produce somewhat higher viscosities than storage underground. Oils D, G, H, K, L, O, Q, and

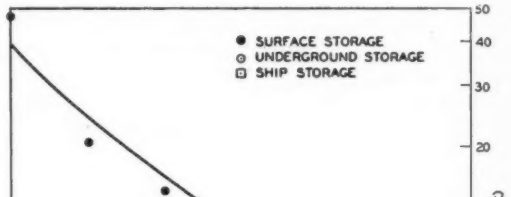

Fig 16

EFFECT OF STORAGE CONDITION ON VISCOSITY–OILS OF 165 SEC REDWOOD I VISCOSITY AT 122° F AND 30° F FLOW POINT

R were very similar to each other and had lower pour points than B and H. Fig 16 gives the viscosities measured on these oils after storage under different conditions. Surface and underground storage fall on the same viscosity/temperature curve, suggesting that with this type of oil there was little difference between these two types of storage. This oil on board ship was more fluid, indicating ships' conditions to be more favourable to the oil.

It was found that the shearing action of fuel oil pumps reduced the viscosity of fuel oils, and this could

account for the better performance found on board ship.

All trials conclusively demonstrated that a co-axial cylinder viscometer was a suitable instrument for assessing the flow properties of a fuel oil at temperatures around its pour point. The detailed design used did not noticeably affect its results, and it was found that commercially available types were suitable. Measurements in instruments similar to the California Research Corporation U-tube did not appear promising. The trials also showed that if the yield value of fuel oils are important they can be best determined by measurements in U-tubes.

As a result of the trials, Panel F developed a pumpability test method for Admiralty fuel oil using the Ferranti co-axial cylinder viscometer. A heat treatment was devised which gave the oils, when tested in the viscometer, the same viscosities as found in the full-scale trials. This work is described by Ackroyd, Hoskins, and Lowe.[9]

ACKNOWLEDGMENTS

The authors thank the Board of Admiralty and the Chairman and directors of the British Petroleum Company for permission to publish this paper. They also thank the many members of the Admiralty depot staff and of Panel F of the Admiralty Advisory Committee who participated in the trials on which this paper is based.

References

[1] Russell, R. J., this symposium.
[2] E-in-C Specification No. 0–1, dated 2.12.53.
[3] Specification DEF 2406, dated 10.7.58—Furnace Fuel Oils.
[4] Gill, F., and Russell, R. J. *Industr. Engng Chem.*, 1954, **46**, 1264.
[5] ASTM Manual on Measurement and Sampling of Petroleum and Petroleum Products, 1953, p. 51.
[6] IP 15/55, Cloud and Pour Point.
[7] Baker, A. J., Tourret, R., and Jones, J. T. *Engineering*, 16.1.59, p. 82.
[8] Wyllie, D., and Taylor, W. E. L., this symposium.
[9] Ackroyd, G. C., Hoskins, D. E. M., and Lowe, A. G., this symposium.

APPENDIX 1

Analysis of Pumping Trial Results

Admiralty fuel is normally pumped at low temperatures under streamline flow conditions. Therefore the Poiseuille equation:

$$\eta_e = \frac{\pi d^4 p}{128\, lQ} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

would be expected to hold. However, at low temperatures the viscosity of Admiralty fuel varies with the applied force and also with time of shearing. Equation (1) may be written as:

$$\eta_e = \frac{pd/4l}{32Q/\pi d^3} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$pd/4l$ is the shearing stress (*i.e.* the force per unit area) at the pipe wall; $32Q/\pi d^3$ is the apparent rate of shear at the pipe wall and is related to the velocity gradient there. The shearing stress and rate of shear define the mechanical conditions under which viscosity is measured. They can be easily controlled in laboratory tests. Thus, when making full-scale trials with Admiralty fuel to correlate with laboratory tests, it was necessary to measure accurately the shearing stress and the rate of shear.

To do this it was necessary to measure:

(1) The flow rate (Q).
(2) The pressure drop (p) making due allowance for change in hydrostatic head. This was done by correcting all pressures to ordnance datum.
(3) The lengths and diameters of the pipe (l and d).

In practice, pipes of differing diameter were found in the test lines. To allow for this equation (1) was generalized as:

$$\eta_e = \frac{\pi d_1^4 p}{128L} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where $L = [l_1 + (d_1/d_2)^4 l_2 + \ldots]$

was taken as the equivalent length of the pipeline in terms of the predominant diameter pipe (d_1).

The shearing stresses and rate of shear were always calculated on the basis of the predominant diameter of pipe and the equivalent pipe length.

All trials were preceded by a careful survey to obtain the pipe lengths and the heights of all test points above ordnance datum.

APPENDIX 2

Estimation of Effect of Varying Temperature Across a Pipe on Flow Resistance

Nomenclature

Q = Flow rate.
p = Pressure drop.
l = Pipe length.
$p^1 = p/l$.
d = Pipe diameter.
η_e = Pipe viscosity.
η_c = Viscosity of warmest oil in pipe.
η_w = Viscosity of oil at pipe wall.
y = Distance from bottom of pipe.
u = Velocity of oil at a distance y from bottom of pipe.
η_y = Viscosity at point y.
A, n = Coefficients giving distribution of viscosity across pipe.

To interpret the full-scale results from the tests in Section I, an equation to indicate the increase in flow resistance caused by cold oil near the walls of the pipe was required. A rigorous solution did not appear possible for a temperature distribution which was not symmetrical about the pipe axis. The following assumptions have been made:

(1) The viscosity distribution on a vertical diameter of the pipe could be applied to an infinite channel whose depth equalled the diameter of the pipeline and a velocity distribution obtained. The velocity distribution on the vertical diameter of the pipe could be obtained by halving the distribution so calculated. (This is the case for central symmetry.)
(2) Lines of equal oil velocity always enclosed circular cross-sections.

Assumption (1) allowed a graphical evaluation of the separation (δ) between lines of equal oil velocity.

From this, assumption (2) allowed the flow rate to be graphically integrated by using the equation:

$$Q = \int_0^d \frac{\pi}{2} u \delta d\delta \quad . \quad . \quad . \quad . \quad . \quad (1)$$

To simplify the calculation the vertical viscosity distribution was assumed as:

$$\eta_y = \frac{\eta_w}{1 + A(y/d) - A(y/d)^n} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The temperature distribution can be obtained from the viscosity distribution by using the viscosity/temperature relation $\eta_T = \eta_0 e^{-\sigma T}$. By suitably choosing A and n most experimentally observed temperature distributions can be well simulated. Substituting $n = 2$ in equation (2) gives central symmetry; in this case the ratio of the viscosity (η_c) of the hottest oil to the wall viscosity is:

$$\eta_c/\eta_w = (1 + A/4) \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Substituting $n = 7$ gives the lowest viscosity oil about halfway between the centre and the top of the pipe; the viscosity ratio then is:

$$\eta_c/\eta_w = (1 + 0{\cdot}583A) \quad . \quad . \quad . \quad . \quad (4)$$

Putting $n = \infty$ gives the lowest viscosity oil at the pipe top and the viscosity ratio as:

$$\eta_c/\eta_w = (1 + A) \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Equations (3), (4), and (5) relate the pipe wall and pipe centre viscosity for three cases which, between them, give close approximations to all the experimentally observed cases.

Using equation (2) to calculate the velocity distribution across the vertical diameter of a pipe gives (using assumption (1)):

$$u = -\frac{p^1 y^2}{2\eta_w}\left[\tfrac{1}{2} + A/3(y/d) - \frac{A}{n+2}(y/d)^n\right] + \frac{p^1 dy}{4\eta_w}\left[\frac{1 + 2A/3 - 2A/(n+2)}{1 + A/2 - A/(n+1)}\right] 1 + A/2(y/d) - A/n + 1(y/d)^n\Big] \quad . \quad . \quad . \quad (6)$$

This equation can be rendered dimensionless by dividing by $\frac{d^2p^1}{4\eta_w}$, giving

$$\frac{u}{d^2p^1/4\eta_w} = -\left[(y/d)^2 + \frac{2A}{3}(y/d)^3 - \frac{2A}{n+2}(y/d)^{n+2}\right] + \left[\frac{1 + 2A/3 - 2A/(n+2)}{1 + A/2 - A/(n+1)}\right] \left[(y/d) + A/2(y/d)^2 - \frac{A}{n+1}(y/d)^{n+1}\right] \quad (7)$$

Graphical solution of the equation gives two values of (y/d) for any chosen value of $\frac{u}{d^2p^1/4\eta_w}$; thus it is possible to determine the difference between them, δ/d, and to form the function:

$$\frac{u}{d^2p^1/4\eta_w} = f(\delta/d, A) \quad . \quad . \quad . \quad . \quad (8)$$

Substituting this in (2) gives:

$$Q = \frac{\pi d^4 p^1}{8\eta_w}\int_0^1 f(\delta/d, A) \,.\, \delta/d \,.\, d(\delta/d) \quad . \quad . \quad (9)$$

The throughput in the line can be defined in terms of the uncorrected pipe viscosity, calculated according to Poiseuille's law, as

$$\eta_e = \frac{\pi d^4 p^1}{128Q} \quad . \quad . \quad . \quad . \quad . \quad (10)$$

Substituting (10) in (9) and rearranging, then gives:

$$\frac{\eta_w}{\eta_e} = 16\int_0^1 f(\delta/d, A)\delta/d \,.\, d(\delta/d) \quad . \quad . \quad (11)$$

The result of graphically evaluating the integral

$$16\int_0^1 f(\delta/d, A)(\delta/d) \,.\, d(\delta/d)$$

at $n = 2$, 7, and ∞ for various values of A is shown in Fig 17.

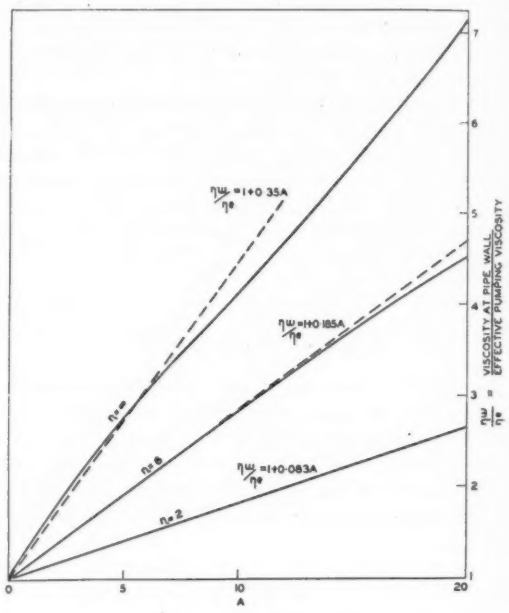

FIG 17

DEPENDENCE OF RATIO $\frac{\text{VISCOSITY AT PIPE WALL}}{\text{EFFECTIVE PUMPING VISCOSITY}}$ ON A AND n

This shows that for these three cases there is an almost linear relationship between η_w/η_e and A. This is, for

$$(\text{for } n = 2)\ \eta_w/\eta_e = 1 + 0{\cdot}083A \quad . \quad . \quad (12)$$

$$(\text{for } n = 7)\ \eta_w/\eta_e = 1 + 0{\cdot}185A \quad . \quad . \quad (13)$$

$$(\text{for } n = \infty)\ \eta_w/\eta_e = 1 + 0{\cdot}35A \quad . \quad . \quad (14)$$

Elimination of A between equations (12) and (3), (13) and (4), and (14) and (5), suggests that for practical purposes the relation between effective pipe viscosity and the viscosities at the warmest point of the pipe and at the pipe wall is

$$\frac{1}{\eta_e} = \frac{1}{3\eta_c} + \frac{2}{3\eta_w} \quad . \quad . \quad . \quad . \quad (15)$$

$$= \frac{1}{\eta_c}\left[1/3 + 2/3\eta_c/\eta_w\right] \quad . \quad . \quad . \quad (16)$$

A knowledge of the temperature distribution across the pipe and the viscosity/temperature relationship for the oil being pumped allows η_c/η_w to be determined, thus giving η_e in terms of η_c.

THE STUDY OF FUEL OIL PUMPABILITY USING A LABORATORY PUMPING RIG *

Prepared by D. WYLLIE † (Fellow) and J. T. JONES † (Associate Fellow) and presented by J. T. JONES

INTRODUCTION

LARGE-SCALE pumping trials in a depot suffer from the disadvantages that the temperature of the fuel cannot be adjusted to any required level before the trial and the pipelines during the trial are exposed to the prevailing air temperatures. In addition, the pipes may have been in use for some years, and their internal condition can only be imagined. In spite of these difficulties, a good deal of information became available as a result of large-scale cold weather pumping trials,[1] but it was decided that a rig should be constructed which would be large enough to reproduce the actual conditions which might exist in a small ship, yet be small enough for the essential parts to be housed in a cold room.

The problems which can usefully be studied in such a rig are:

(*a*) The clearing of a line of gelled oil.

(*b*) The pumping rates achievable with fuels of differing types at temperatures which might occur ashore or on board ship.

(*c*) The rate of breakdown of a gelled or near-gelled fuel when it is pumped along a pipe.

(*d*) The relation between apparent yield value, rate of flow, and apparent viscosity in the pipe, and yield value and apparent viscosity measurements in laboratory apparatus.

In such a rig it should be possible to conduct repeated line clearing experiments to work at any temperature in the required range and, by a suitable choice of pipe length and diameter, to obtain the required range of shear stresses and rates of shear. It should also be possible to set up the rig in such a manner that any marked breakdown of " structure " and apparent viscosity of the fuel, as it passed down the pipe, would be detected and not masked by the imperfection of the pipe system, the possibility of air-locks, and the difficulties of measurements in the field.

DESCRIPTION OF RIG

An instrumented length of 4-inch internal diameter pipe was connected to the suction side of a pump, the instrumented length being contained inside a temperature-controlled room. Six storage tanks were provided outside the room, and one inside the room; all tanks could be connected to the suction side of the pump either directly or through the instrumented length, or to the discharge side of the pump. Provision was made for measuring temperatures, pressures, and flow rates, all indicating instruments being concentrated at one spot outside the room for easy use during experiments. The layout of the rig is shown in Fig 1. Fig 2 shows the coil and the original inside tank during construction.

The pipe systems were made from 4-inch internal diameter hot finished steel pipe, and all isolating valves were gate valves. The instrumented length was 133 ft long and was fitted as a rectangular coil of constant rise with all bends of at least 1 ft radius to reduce bend effects. The internal storage tank, holding approximately 450 gallons, was situated in the centre of the coil and was connected to the coil at the bottom. Each end of the 133-ft length was fitted with a vertical branch, holding a transparent glass tube rising to a height of about 4 ft from the lower part of the coil. Suitable vents and drains were situated in convenient positions.

The six external storage tanks were of 500 gallons capacity and were fitted with dip rods calibrated to read in 1-gallon intervals. Each tank contained a steam coil for heating, suction and drain connexions at the bottom, and a filling connexion and a connexion from the discharge side of the pump at the top. One tank, No 2, was fitted with one additional pump discharge connexion at a lower level, to enable oil to be discharged below the oil level when required to prevent the entrainment of air.

A 4–5-inch motor-driven Drysdale Vertoil pump was used and this was driven by a d.c. motor, limited speed control being available by means of a variable resistance in the field circuit. The pump was of the gear wheel type and was considered to be typical of those used in transferring fuel oil. Initially a flowmeter was situated on the discharge side of the pump; this was a Brodie-Kent X77 positive displacement meter of the semi-rotary piston type. This flowmeter had been used on previous large-scale trials and was known to give the required accuracy. The quantity of oil passing the flowmeter was indicated on a direct reading counter graduated in tenths of a gallon. With this arrangement the flow rate through the coil could be controlled by varying the speed of the pump. For the lower flow rates, a Comet 1¼-inch positive displace-

* MS received 29 October 1959.

† Admiralty Oil Laboratory, Brentford, Middlesex.

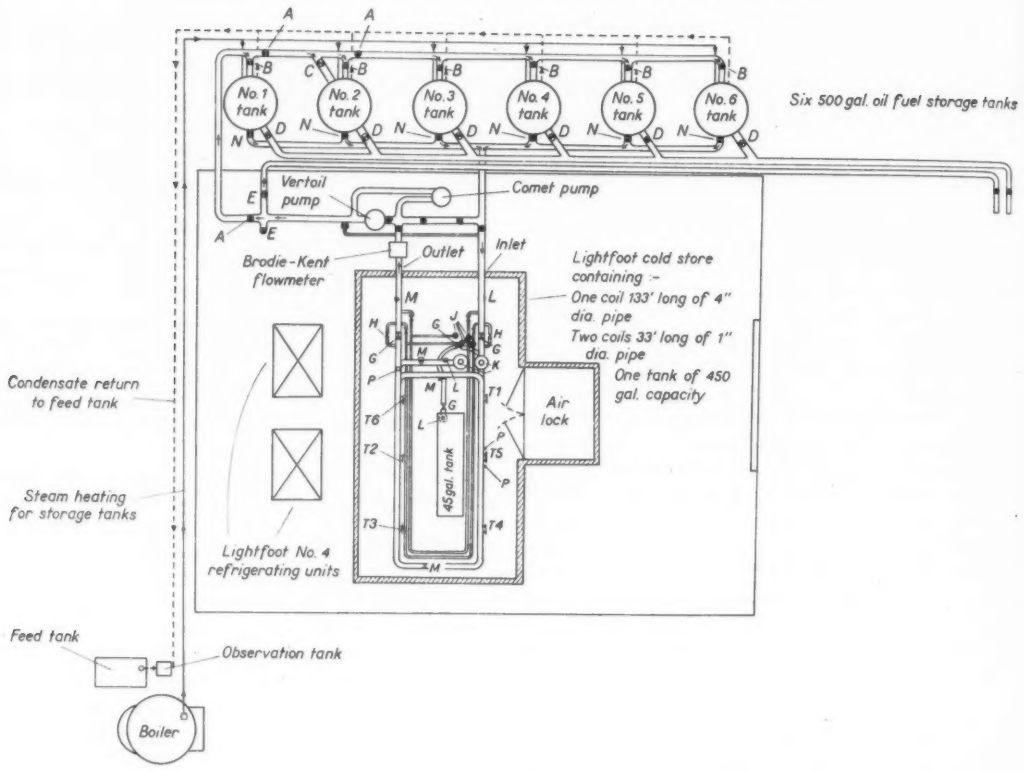

FIG 1

GENERAL ARRANGEMENT AND LAYOUT OF THE ARCTIC TRIALS R16

ment pump was installed, parallel to the larger pump. This pump contained spring-loaded vanes, running in an eccentric housing. At a later date it was desired to operate the rig by maintaining a constant pressure drop across the coil. This could be done only by permitting the pump to take its suction directly from an outside tank at the same time as from the coil, and by varying the quantity of oil reaching the pump from the outside tank. It was therefore necessary to reposition the flowmeter adjacent to the coil, *i.e.* on the suction side of the pump before the direct connexion to the outside tanks. With this modified layout the larger pump was found to give the necessary control and the smaller pump was no longer used.

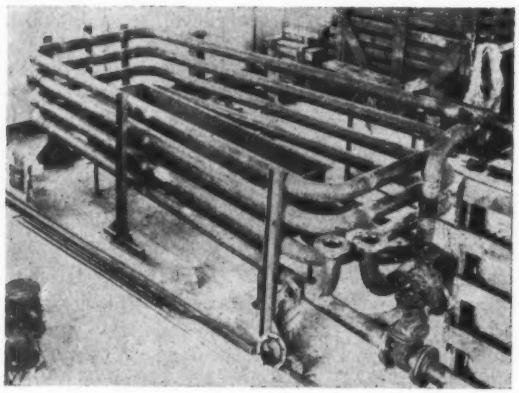

FIG 2

VIEW OF COIL BEFORE CONSTRUCTION OF COLD ROOM

TABLE I

Oils Studied in Rig

Oil No	37	22	43
Flow point, ° F	50	30	45
Redwood viscosity at 122° F, sec	110–120	180	180
No 1	Used in large-scale pumping trials. Included under above code No in paper on storage conditions	Studied by AOL staff at depot. Included under above code No in paper on storage conditions	Residue from large tank of oil. (Flow point 35, Red. visc at 122° F, 170 sec) taken for Arctic cruise referred to in paper on pumping trials
History			

The 133-ft length of the coil was fitted with transducers for indicating pressures at six points, as evenly spaced along its length as practicable. Branch connexions were made at each point so that the transducer heads were in line with the inside wall of the

pipe and did not obstruct the flow. The transducers were Salford Electric Company instruments and the pressures were indicated on distant reading galvanometers mounted on a panel outside the temperature-controlled room. Each transducer was calibrated to read pressures from +5 to −15 psi to an accuracy of ±1 per cent of the full-scale reading (±0·2 psi). These instruments had also been used previously at full-scale pumping trials when it had been found that an accuracy better than the above was usually obtained.

All temperatures were measured by copper–constantan thermocouples connected to 12-point Honeywell Brown potentiometric recorders stamping every 36 seconds. Each 500-gallon storage tank and the 450-gallon internal tank was provided with seven thermocouples, and couples were also provided at the inlet and outlet of the coil and pump. Additional thermocouples were supplied at different points in the room (see Fig 1), in the wall of the pipe at point No 6, and for use with the laboratory instruments such as Ferranti and conicylindrical viscometers and CRC tubes, also situated in the room. As temperature measurements were not required from all the external tanks at any one time, the points on the recorders were distributed to read the temperatures required for the particular experiment.

It was also required to measure temperatures across the pipe in some of the experiments. Three points were selected; one between transducer points Nos 1 and 2, one between transducer points Nos 3 and 4, and one at transducer point No 6. Three thermocouples were fitted at each, evenly disposed horizontally across the pipe at the first two points and vertically at point No 6. These were connected to two further recorders, of 6-second interval stamping, and positioned to give a continuous picture of the temperature distribution across the pipe at these points.

The temperature-controlled room was a standard Lightfoot 40-ton food store. The cooling system was in three parts. First, a refrigerator unit, employing Arcton 6 as the refrigerant, cooled brine in the brine tank; secondly, the brine was circulated around coils in a compartment of the room; and thirdly, two 12-inch fans circulated air over the brine coils and through the main part of the room, on a closed cycle. A resistance wire heating element, supplied with current through a variac, was situated on the air inlet side of the fans and provided the necessary heat for the higher temperatures.

The refrigerator unit was controlled by a coarse thermostat in the brine tank which could be set by hand. The temperature of the brine pumped through the brine coils was regulated by permitting varying quantities of brine to re-pass through the coil without passing through the brine tank; this was performed by an automatic by-pass valve operated through an electronic panel controlled by two sensitive thermostats in the main part of the room. The set point (*i.e.* the temperature required in the room) was regulated by setting a potentiometer fitted on the electronic panel. This potentiometer was operated by an oscillating follower on a cam, which was of the form of an Archimedean spiral and could be set in one position, or rotated to reduce the set point by 1° F per day between 60° and 32° F.

A 1-inch diameter pipe of the same length/diameter ratio as the 4-inch pipes was also constructed, but has not been used so far.

The electrical supply to all the instruments used was controlled by a voltage stabilizer.

BASIS FOR OPERATION OF THE PUMPABILITY RIG

An installation such as has been described could be regarded merely as a means of simulating typical service conditions, such as time of cooling before pumping and applied shear stress, in order to ascertain whether selected fuels could be pumped under the conditions postulated. In addition, it was desired to learn more of the relationship between practical pumping and measurements made in laboratory apparatus.

The items on which information was required were reduced to three.

(1) The minimum shear stress required to produce flow.

(2) The time required to achieve a steady rate of flow.

(3) The steady flow rate which could be achieved with the forces available.

The large-scale field trials [1] gave the following information:

(*a*) Flow could be expected once the yield value of the oil as determined in laboratory yield value tubes had been exceeded. To this was added the rider that flow could even commence after many hours pumping when the average shear stress along the line initially gelled was less than the yield value determined in small yield value tubes.

(*b*) The rate at which the flow increased could be deduced by direct comparison with the increase of shear rate when the oil was subjected to a constant shear stress in a coaxial cylinder viscometer.

(*c*) Pipe viscosities, once steady flow conditions had been established, were normally about the same magnitude and probably never more than twice equilibrium viscosities determined in coaxial cylinder viscometers at the same rate of shear.

Examining more closely the factors involved, Bingham [2] showed that a gelled fluid in a pipe commences to flow when the shear stress at the pipe wall exceeds the yield value. This was elaborated by Buckingham [3] into an equation to describe the flow of the

fluid as the plug moves along the line and slowly breaks down. His treatment, however, assumes that the fluid has a unique viscosity for each applied stress, not a viscosity which changes with time of shearing. At the time the Panel's work commenced, little useful information was available as to the properties of time-dependent fluids.

It is known that visible flow does not commence immediately stress is applied to a gelled fuel unless the stress is well above its yield value. It has been suggested that the delay is caused by the high initial viscosity of the fuels and the time required for the movement to reach measurable dimensions. This has led to discussion as to how much movement in a 4 inch (or larger) pipe shall be regarded as equivalent to the initial movement detectable in a narrow ($1\frac{1}{2}$ mm) yield value tube. So far the possible distortion of the gel before yielding has not been considered at all. Billington's [4, 5] treatment of the gelled fluid as visco-elastic involves the assumption that the gel will distort in response to any applied stress until the strain equals the stress or the elastic limit is passed and flow commences. This envisages movement under stress before the point is reached at which flow commences.

The $1\frac{1}{2}$-mm diameter yield value tube originally described by Gill and Russell [6] and employed by the AFLAC Panel [7] was the principal apparatus employed to determine yield value. A few results were obtained in the 1-cm diameter tubes described by workers at the Californian Research Station [8] and referred to herein as CRC tubes. These have been claimed to be less liable to error owing to the possible presence of air bubbles than are the narrow bore yield value tubes. As only a few results are so far available, these are not included in this paper.

Voids and air bubbles can also occur in a large pipe, especially if the oil is cooled in a pipe, both ends of which are sealed. The stand pipes were used as a reserve of oil to permit the pipe to be cooled with the valves at each end shut. Once the oil gels it is still subject to strain caused by expansion and contraction, with fluctuation in the temperature of the cold room, even although these may not exceed $\pm 1^\circ$ F.

Both the AFLAC Panel's yield value method [7] and the CRC method apply shear stress increasing in steps by about 30 dynes/cm^2 every five minutes. The Panel's method takes yield value as the shear stress at which first movement is observed. This is likely to be high, as insufficient time is permitted for visible movement to take place, whether this delay is ascribed to purely viscous effects or to visco-elastic effects. An alternative procedure, therefore, is to subject a series of tubes to a series of shear stresses, one shear stress per tube, and note the time that elapses till movement occurs.

In practice, it is required to know the shear stress at which flow in a pipe will commence in a " reasonable time," which must obviously be defined for the purpose in hand. It was considered that ships' staff would not take kindly to a situation in which no measurable flow occurred in 30 minutes or at most one hour after starting up.

It was decided after preliminary trials not to attempt to determine minimum yield value in the 4-inch pipe, since, on the one hand, this would entail increasing the shear stress applied to the pipe by small increments at intervals of one hour or more and would be very time-consuming, and on the other hand, would upset the time scale for the subsequent pumping of the line. It had been intended to conduct the yield value experiments via the stand tubes, then switch to the main pump once some movement of oil had already occurred. Instead, each run was conducted by putting a suction on the line using the main pump and operating it and the valve system to give some definite pressure drop down the line. The flow obtainable on start-up and the rate of breakdown was to be compared with the results obtained in constant shear stress coaxial cylinder viscometers.

Experiments were carried out under two conditions. First, with a gelled line and tank full of gelled oil, *i.e.* both line and cold room tank filled and cooled until both had ample time to stabilize at cold room temperature. On pumping, the oil initially in the pipe was continually replaced by cold oil from the tank. The second condition was that in which the line was cold and gelled, the cold room tank containing warmer fluid oil. This condition could occur in a depot if the lines were left full of oil in the winter, or in a ship when the pipe passes through flooded compartments. Under this condition, as the plug of cold oil passes through the pipe it is replaced by fluid oil of much lower viscosity. Even if the total pressure drop from cold room tank to pump was held constant, this pressure would largely be confined to a shorter and shorter plug of cold oil. The shear stress on this plug would rise, and it would ultimately leave the line rapidly.

It was decided to attempt to simulate both conditions in the programme. A further step was to fit groups of three thermocouples across the pipe at three points and connect these to high-speed recorders to establish in the line clearing experiments when the warm oil displaced the cold oil and whether it did so on an even front.

Once steady flow was established, the field trials indicated that the pipe viscosity may be expected to be the same as, or at most twice, the laboratory equilibrium viscosities at the same rate of shear. The rate of shear was selected by applying Poiseuille's equation to the flow, *i.e.* no account was taken of the non-Newtonian characteristics of the oil. This is an empirical rule based on field experiments. It was also found in the field that the disturbing effect of drawing the oil from the tank into the pipe and accelerating it

from rest to the rate of flow in the pipe must have done a substantial amount of shearing. It was observed that pressure drops, and therefore shear stresses, in the first section of the pipe were sometimes greater than those further along, but within the possible error, normally about 25 per cent, it was not possible to detect any further decrease of shear stress as the oil passed down the pipe.

It was considered that direct observation of pressure drops along our 4-inch pipe would confirm the presence or otherwise of substantial breakdown as the oil moves down the pipe. In order to perform viscosity measurements at constant rates of shear, steel beakers of about the same diameter as the pipe were filled each time the pipe was filled and left in the cold room. In addition, steel beakers were hung in the cold room tank at various levels to retain oil from these levels when the tank was pumped out. Several Ferranti portable viscometers were employed on these samples. These viscometers were not left continuously in the cold room, but were placed gently in position in the samples to be tested on the day before they were operated.

PRELIMINARY PROVING RUNS

In order to gain experience with the control of the rig and to ascertain the actual pipe diameter and the possible error of the various instruments, a number of pumping runs were conducted using a heavy fuel oil which behaved as a Newtonian fluid at temperatures above 40° F. From these it was observed that:

(*a*) The true internal diameter of the test coil installed in the cold room was 3·96 inches (±0·04), and the nominal internal diameter of 4 inches could therefore be used in calculations.

(*b*) The pressure transducers were stated to give an accuracy of ±0·3 psi on any pressure difference between two points on the coil, and if frequently calibrated would give pressure differences which were accurate to ±0·2 psi.

Note: The results had to be considered in relation to the following:

Average shear stress over pipe	*Pressure drop between points 1 and 6,* i.e. *over whole length*
150 dynes/cm²	3·4 psi
300 ,,	6·8 psi
500 ,,	11·5 psi

A pressure difference of 0·2 psi over sections of the pipe was equivalent to a shear stress of:

Points	*1 to 6*	*1 to 2*	*2 to 3*	*3 to 4*	*4 to 5*	*5 to 6*	*4 to 6*
Shear stress, dynes/cm²	9	50	40	45	37	57	22

(*c*) Rates of flow could be read to an accuracy of ±1 per cent and a flow of 0·02 gallon could be detected at low flow rates.

(*d*) Temperatures could be read with the Honeywell Brown recorders to about ±0·5° F.

(*e*) The cold room temperature variation over the whole room was about ±1° F of the required temperature.

(*f*) The centre of the cold room tank cooled more slowly than the pipe. In order to improve heat transfer, metal sheets were hung at intervals in the cold room tank during later runs.

The calibration oil then in tank No 6 was heated by means of the steam coils and pumped round the whole circuit until the temperatures everywhere reached 100° F. As much of the oil as possible was pumped into tank 6; much of the remainder drained into the cold room tank and was removed with a portable pump. The rest was drained through the valves provided for this purpose. The draining took more than one day to complete, and the oil cooled during this time. The pipework inside the cold room was thoroughly drained by raising the cold room temperature to 80° F and allowing the pipes to drain at this temperature for two or three days. The cold room tank was then cleaned out by hand. The pipework outside the cold room was flushed with the minimum quantity of the first test oil, which was stored ready for use in external storage tanks 1 and 2; the washings were pumped to tank 5 and were then drained again. The lowest parts of the pump were cleaned by hand. No further flushing was considered necessary, but the new oil was pumped around the system for about one hour to ensure that any remaining thin film of the old oil was thoroughly mixed with the new. This type of change-over procedure was followed each time the rig was filled with a new test oil.

The first test oil, known as No 37, was then filled into both pipe and cold room tank and into various instruments and the cold room set to cool down to 36° F. After 14 days, when the oil was pumped out, the pipe had reached 36° F but the bulk of the oil in the cold room tank had a temperature of about 38° F. In the next run the oil was allowed 21 days to attain a test temperature of 38° F and was then pumped after some preliminary work with yield value tubes.

In these two runs (Nos 42 and 43) the suction rose rapidly to the maximum available and became concentrated along the line of cold oil in the cold room, giving a shear stress between points 1 and 6 of nearly 600 dynes/cm² when flow commenced. Once flow commenced and cold oil flowed as far as the pump, the available pressure drop was divided more evenly down the whole line. When steady flow rate had been established the shear stress between points 1 and 6 was between 420 and 460 dynes/cm², the exact figure depending on the head of oil in the cold room tank, the pump exerting maximum suction all the time.

Further runs were done after the flowmeter was transferred from the delivery to the suction side of the pump, being now sited as shown in Fig 1. It was

now possible to hold a pressure drop up to that equivalent to an average shear stress of 400 dynes/cm² between points 1 and 6, for the duration of a pumping run. Run 45 was conducted to confirm this, oil which had been in the cold room for some months while the rig was not in use being used for this purpose.

OUTLINE OF MAIN PROGRAMME

After study of the requirements it was decided to concentrate on work at 36° F with subsidiary work at 48° and 32° F. It was decided that at 36° and 32° F it should be assumed that the available shear stress was limited to 300 dynes/cm². Pumping would therefore be attempted in the first instance with a pressure drop equivalent to this shear stress. In some runs at 36° F both pipeline and cold room tank would contain oil at 36° F. Pumping would take place at 300 dynes/cm², and once steady flow had been achieved and the results recorded, the remainder of the oil in the cold room tank would be pumped using the maximum suction available. The other runs at 36° F would be line-clearing runs; the cold room tank would not be filled until the oil in the pipe had been allowed sufficient time to gel at 36° F, then oil, probably at 50° to 65° F, would be pumped into the cold room tank from the outside storage tanks and line clearing attempted at 300 dynes/cm². The runs at 32° F would be line clearing only. The runs at 48° F, the temperature selected for the proposed specification pumpability test, would be conducted at 150 dynes/cm², and if a steady flow rate were achieved would be completed at 300 dynes/cm². No line-clearing runs were to be attempted at 48° F.

The time allowed for the oil to cool was arrived at on the basis that in practice a line of oil at 36° F would not normally be left undisturbed for more than two to three days, but would be turned over or emptied. From this, three days at 36° F, or two days at 32° F, became a reasonable time of cooling for the line-clearing runs. If the line was cleared easily the experiment would be repeated after a longer time of cooling. It was known that the oil in the centre of the cold room tank would take several days to attain 36° F with the oils selected for test. In order to promote heat transfer, steel plates were suspended vertically in the tank at intervals of about 18 inches, leaving at least a foot unobstructed at the bottom. Nevertheless, the tank centre still cooled considerably slower than the pipe. It was decided that the oil in the tank should be permitted ample time to attain a structure similar to that of the oil in the pipe and, in general, three weeks' cooling was aimed at when both tank and pipe were brought to the same temperature. Some variation took place, as it was not possible to adhere rigidly to this time owing to other commitments.

It was appreciated that the oils would be sheared by passage through the pump when the pipe system and cold room tank were filled before each run. In summer the oil would probably be at a temperature of 60° to 70° F on filling. It was decided that in winter the oils should, if possible, be raised to 55° to 60° F by continual circulation through the pump before charging the system. In addition, oil was on two occasions heated to over 90° F using the steam heating coils before charging the system. Normally the cold room temperature was 55° to 60° F at the time of filling, but on a few occasions it was brought to the test temperature before filling. The cold room cooled from 55° to 60° F to 36° F overnight. The pipeline could be expected to attain the test temperature in one to two days, but the oil in the centre of the cold room tank, even after the metal plates were put in, took seven to twelve days to attain the test temperature.

The oils selected for this work were all known to have some particular feature which might make them difficult to pump at 36° F. The first, No 37 [9] had the highest flow point permitted for Schedule 390-A oils and a Redwood viscosity at 122° F above the maximum of 100 sec permitted for oils at this flow point. It was therefore likely to thicken rapidly at temperatures below 50° F, and from the large-scale pumping trials [1] was known to have held a bulk temperature of 51° F in a storage tank in February 1955 owing to gelation of the outer few feet of oil.

The second, No 22 [9] was within the limits permitted for Schedule 390-A oils, but was known to have formed gelled outer layers in winter in tank storage. The general viscosity level of the oil also increased much more rapidly with decreasing temperature than most other oils of similar flow point. Warming destroyed the structure, with consequent substantial drop in apparent viscosity at storage temperatures, and the structure did not quickly re-form. It was therefore of interest to see how this, one of the most viscous oils in tank storage which could be purchased under current specifications, would behave in the rig.

The third oil, No 43, also had an interesting history. After 2½ years storage underground, it had a viscosity of about 10 poise at 50° F, then in its last nine months in store was found to have approximately doubled in viscosity. The bulk of the oil was taken on board a tanker steaming to Arctic waters and was used in a pumping trial. This trial is described in the paper on large-scale pumping trials.[1] Neither when first pumped on board nor after cooling to 43° F during ten days in Arctic waters did this oil recover the structure or viscosity level indicated by the last samples taken ashore. The tanker's full cargo was issued to HM Ships, and only a small amount of oil remained in the reservoir ashore. Moreover, this residue was appreciably thicker than the bulk supply and failed to meet the flow point/viscosity requirements for Schedule 390-A oils. Nevertheless, it was

considered worthwhile to see how this residue would behave in the rig.

Oil No 37—Runs 42 to 54 (Tables II and III)

The three preliminary runs with both line and cold room tank filled with cold oil have already been mentioned. It was decided to re-start the programme with a run at 48° F. The oil flowed readily under 145 dynes/cm², and when the shear stress was raised to 300 dynes/cm² the cold room tank was emptied in a few minutes (Run 46).

Attention was now concentrated on 36° F, starting with line-clearing runs. For these, fresh thermocouples were inserted in the line and some difficulty was experienced in obtaining a vacuum-tight seal at the thermocouples near point 6, the end of the observed section nearest the pump. In the first line-clearing run (No 47), when full pump suction was applied, a leak developed at this point which rendered the flowmeter readings useless. The line was therefore cleared and repairs executed for a repeat effort (Run 48). The leak, although much smaller, was still sufficient to upset the flowmeter, and although the run was carried through, taking the flow rate from tank dips, the results may be affected by air in the pipe. Even a small volume of air at atmospheric pressure represents a substantial volume at low pressure. In all subsequent runs regular dips were taken in the outside tank in order to detect any air leaks in the system.

It appeared that after seven days at 36° F one hour was required to clear the line, using maximum available suction. Two further line-clearing runs followed, both after only three days cooling. In Run 49 the line was cleared in 18 minutes using maximum suction; in Run 50, 58 minutes was required using about 300 dynes/cm² overall shear stress. Both cold room tank and pipe were then filled with oil and allowed 16 days to stabilize at 36° F. The line could still be cleared at about 300 dynes/cm², but 75 minutes were required (Run 51). An attempt was then made to clear the line after pipe only had been brought to 32° F (Run 52). After only two days considerable difficulty was experienced in clearing the line, about 140 minutes being required, even to reach a flow rate of 0·1 gal/minute, and it was considered that with a few more hours cooling, or only slightly less applied shear stress, the line might not have been cleared.

For the next two runs the oil was heated to over 90° F, then both tank and pipeline brought to 48° F (Run 53) and to 36° F (Run 54). A new difficulty was encountered when the time came to pump the oil at 48° F under 150 dynes/cm². Air temperatures in the hut housing the cold room were so low that the line between the cold room and the pump was 32° F and the oil in the tanks outside was several degrees colder. Although some flow took place immediately, it did not exceed 0·2 gal/min in 66 minutes. The applied shear stress was then stepped up to nearly 200 dynes/cm², which cleared the line slowly, and a steady flow rate was eventually reached. The run at 36° F

TABLE II

Summary of Line-clearing Experiments with Oil 37

Run No	Date	Line temp, ° F	Thermal history			Temp of oil pumped into cold room tank on day of run, ° F	Overall shear stress		Time in min to reach flow rate of			Time in min to clear line	Conditions in line a few minutes after line cleared		Remarks
			Temp of oil on filling, ° F	Time to reach test temp	Time before pumping, days		Aimed at, dynes/cm²	Achieved, dynes/cm²	½ gal/min	1 gal/min	5 gal/min		Rate of flow, gal/min	Shear stress, dynes/cm²	
47	8.10.58	36	61	About 14 hr	9	52	Max available	Nearly 600 falling as flow commenced	>15	—	—	—	—	—	No other records as serious air leak developed at gland
48	21.10.58	36	63	About 12 hr	7	52	Max available	About 575 falling as flow commenced	50	56	60	61	About 50	About 250	Pressure drop in line changes rapidly as gelled oil is cleared out. Air leak not completely cured
49	10.11.58	36	55	About 24 hr but within 2° in about 12 hr	3	54	Max available	About 575 falling as flow commenced	7	9	14	18	About 70	About 250	Pressure drop in line changes rapidly as gelled oil is cleared out
50	13.11.58	36	49	About 8 hrs	3	46	300	315 ± 10	30	45	54	58	About 54	About 275	
52	12.12.58	32	62 Maintained at about 60° F over night before commencing to cool	About 30 hr but within 2° in about 15 hr	2	46	300	290 ± 25	220	260	283	285	About 22	About 320	Immediately after the line cleared the temp of the oil coming from the cold room tank dropped from 46° F to about 40° F
									Took 140 min to reach 0·1 gal/min						

TABLE III

Summary of Experiments with Oil 37 in which both Line and Tank in Cold Room were Filled and Cooled Together

Run No	Date	Temperature, °F		Thermal history				Overall shear stress		Time in min to reach flow rate of			Time in min to pump line capacity	Conditions once steady flow had been established				
		Line temp	Cold room tank	Temp of oil on filling, °F	Time to cool to test temp		Time before pumping, days	Aimed at, dynes/cm²	Achieved, dynes/cm²	½ gal/min	1 gal/min	5 gal/min		Flow rate, gal/min	Rate of shear, sec⁻¹	Shear stress, dynes/cm²	Pipe viscosity, poise	Temp, °F
					Line	Tank centre												
42	9.8.57	35–36·5	35–38	Probably about 60	About 4 days	Not at 35° F after 14 days For first three days cold room set at 50° F	14	Max available	550 falling as flow commenced	6	8	17	22	8·1 7·6 7·2	5·9 5·5 5·2	425 420 410	73 77 79	37·5 38 38
										Line filled first with oil at 36° F then temp rose to 38° F								
43	10.9.57	37·5	37·5–38	Probably about 60	—	—	21	Max available	580 falling as flow commenced	10	11	18	26	7·7	5·6	455	81	38
45 A test of ability to control shear stress	31.7.58	36	36	No record: oil had been in cold room at temp between 36° and 70° F for some months			7 after control set for 36° F	150	155 ± 20	No flow in 20 min				—	—	—	—	—
								200	200 ± 20	No flow in 25 min				—	—	—	—	—
								300 (For 10 min)		Flow commenced at less than 0·2 gal/min				—	—	—	—	—
								350	350 ± 25 except for few min at 400	18	22	—	52	2·7	2·0	345	173	36
										Time taken from raising shear stress to 300 dynes/cm²								
46	16.9.58	48	48	63	18 hr but within 2° in 8 hr	11 days	25	150	145 ± 12	1	2	6	16	9·4	6·9	145	21	48
								Till steady flow achieved										
								300 (for 6 min only)	Approx 300	—	—	—	—	About 36	About 26 (Insufficient oil available)	About 300	About 11	48
51	3.12.58	35·5–36	35·5–36	55	About 24 hr	About 8 days	16	(1) 300	290 ± 15	25	44	—	75	3·2	2·4	280	120	36
								(2) Max Available	About 400	—	—	—	—	6·6	4·9	390	79	36
53	14.1.59	46·5	46–48	95	Cooled to 48° F then temp rose to 66° F on 15th day owing to breakdown. Reset back at 48° F in		21	(1) 150	135 ± 5	Flow only reached 0·2 gal/min in 66 min				—	—	—	—	—
								(2) 200	180 ± 15	82	102	150	130	6·0	4·4	190	43	48
					About 12 hr	About 4 days				Line between cold room and pump at about 30° F believed to be governing flow in first 150 min								
54	25.2.59	37·0	35·75–36·25	95	About 7 days	About 13 days	23	300	315 ± 10	More than 145 min								37·0
								400	415 ± 15	—	20	55	45	5·0	3·7	415	111	37·0
								300	330 ± 10					2·6	1·9	325	171	37·0

TABLE IV

Summary of Experiments with Oil 22

Run No	Date	Line temp, °F	Thermal history			Temp of oil pumped into cold room on day of run, °F	Overall shear stress		Time in min to reach flow rate of			Time to clear line, min	Condition once steady flow was established			
			Temp of oil on filling, °F	Time to reach test temp	Time before pumping, days		Aimed at, dynes/cm²	Achieved, dynes/cm²	½ gal/min	1 gal/min	5 gal/min		Rate of flow, gal/min	Shear stress, dynes/cm²	Rate of shear, sec⁻¹	Pipe viscosity, poise
55	7.4.59	47·5	77	4 days	21	—	150	175 ± 10	4	5	21	22	5·2	175	3·9	45
						—	300	315 ± 5	—	—	—	—	15·9	315	11·8	27
56	30.4.59	36	55	10 days	24	—	300	315 ± 15	34	42	—	66	3·6	320	2·9	110
						—	400	390 ± 10	—	—	4	12	6·5	390	4·8	81
57	24.6.59	36	68	6 days	49	—	300	320 ± 15	117	138	—	166	2·2	320	1·65	194
						—	400	400 ± 15	—	—	—	—	3·80	395	2·8	141
58	29.6.59	36	62	36 hr	3	73	300	290	3	6	15	18	Line clearing			
59	9.7.59	38	68	36 hr	8	75	300	320	8	10	15	18	Line clearing			
60	20.7.59	32·5	65	30 hr	7	67	300	330	63	80	89	91½	Line clearing			
61	22.7.59	32	62	12 hr	2	68	300	305	28	37	51	52½	Line clearing			

TABLE V

Summary of Runs with Oil 43

Run No	Date	Line temp, °F	Thermal history			Overall shear stress		Time in min to reach flow rate of			Time to clear line, min	Condition once steady flow was established			
			Temp of oil on filling, °F	Time to reach test test temp	Time before pumping, days	Aimed at, dynes/cm²	Achieved, dynes/cm²	½ gal/min	1 gal/min	5 gal/min		Rate of flow, gal/min	Shear stress, dynes/cm²	Rate of shear, sec⁻¹	Pipe viscosity, poise
62	2.9.59	43·5	64	8 days to reach 52°. Maintained at 52° for 7 days. Cooled in 10 days to 44° F. Pumped 5 days later.	30	130 330	110 ± 10 300 ± 5	208	274	—	264	1·4 10·4	115 305	1·04 7·7	111 40
63	7.10.59	36	57	24 hr	21	300 400	280 ± 10 370 ± 5	60	75	—	115	1·75 3·6	280 375	1·3 2·65	216 142

took place with air temperatures about 50° F when this difficulty was not encountered. The line had been cooling for 23 days, and after 145 minutes flowed only at 0·3 gal/min at about 300 dynes/cm². It was therefore pumped at about 400 dynes/cm² till steady flow had been established, then the run completed at 300 dynes/cm².

These runs established that there was a reasonable possibility of clearing a line of this oil at 36° F using 300 dynes/cm² shear stress after one week's cooling, but after three weeks difficulty might be experienced.

Oil No 43—Runs 62 and 63 (Table V)

The first of these was intended to simulate the actual rate of cooling of the oil which had occurred on board the tanker in the Arctic cruise. After stabilizing at 52° F, the temperature at which the oil was loaded on board the tanker, the cold room was cooled at a steady rate to bring the pipe and, if possible, cold room tank also, down to 44° F in ten days. It was then pumped at the two shear stresses employed in the trial at sea. It was realized that this oil was more viscous than that actually taken on board ship, but it was not

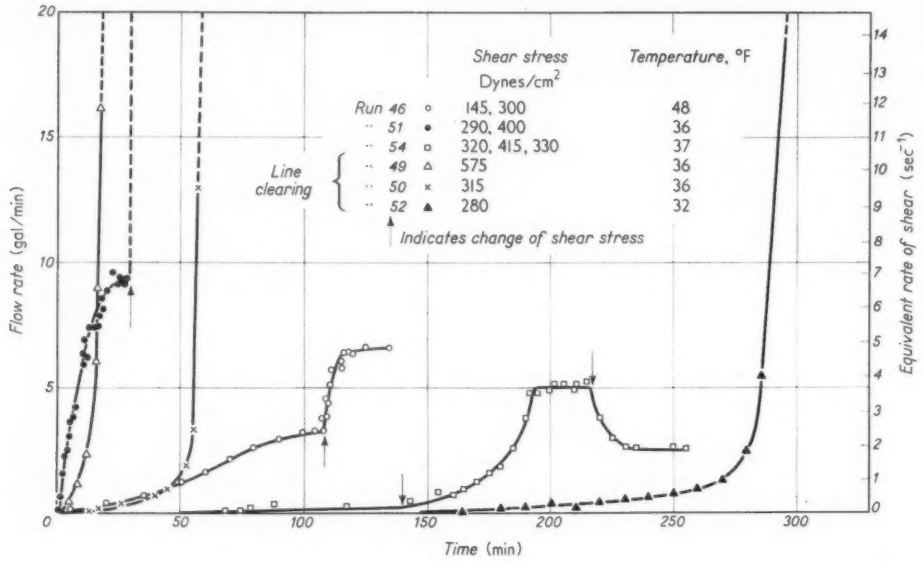

FIG 3

FLOW RATE FOR RUNS WITH OIL 37

It would not be a reasonable risk to allow a line of this oil to cool to 32° F even for two days if only 300 dynes/cm² were available to clear it. These runs also supplied data on probable pumping rates. Typical flow curves are shown in Fig 3.

Oil No 22—Runs 55 to 61 (Table IV)

This oil was pumped first (Run 55) after line and cold room tank had been given three weeks to stabilize at 48° F, then at 36° F (Run 56). Pipe viscosities at 36° F were high, but not as high as the condition the shore storage tank concerned had indicated. The pipe and cold room tank were therefore given seven weeks to cool and stabilize at 36° F and pumping was again attempted at 300 dynes/cm² (Run 57). 70 minutes elapsed before the flow rate even reached 0·1 gal/min, and pipe viscosities were now considerably higher. The remaining four runs were all line-clearing runs which established that this oil took longer to become difficult to pump at 36° or 32° F under 300 dynes/cm² than the previous oil.

expected that it would take nearly 70 minutes to reach a flow rate of 0·1 gal/min at a shear stress of 110 dynes/cm² and 265 minutes to clear the line.

The second run with this oil was with both line and cold room tank at 36° F. The results are set out in Table V.

Conditions in the Pipe

Direct information on this was limited to flow rate, pressure, and temperature. The contrast between line clearing and pumping with both pipe and cold room tank at the same temperature is clearly shown in Fig 3. Pressure measurements demonstrated the concentration of pressure on the cold oil as it moved down the pipe, followed by the warmer oil, with consequent rapid increase in flow rate as the warm oil came down the pipe. For example, in Run 61 the total pressure drop was equivalent to an average shear stress of 320 dynes/cm² until the gelled oil at 32° F had been replaced by warmer oil at 55° F; after 50 minutes pumping the average shear stress between

points 1 and 4, then full of warm oil, was 100 dynes/cm², whereas that between points 4 and 6, which still contained cold oil, was over 600 dynes/cm².

Penetration of warm oil down the pipe was followed by noting the change in pressure drop when this comparatively low viscosity oil replaced the cold oil. It was also followed by noting temperature changes. The sets of three thermocouples placed across the pipe near point 1, between points 3 and 4 and near the

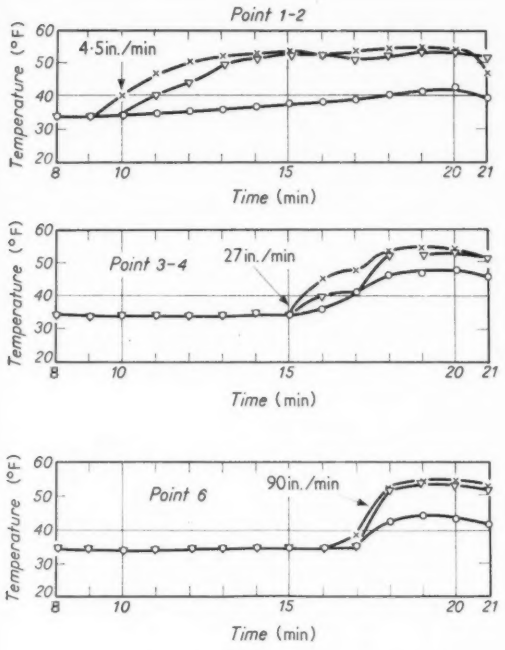

FIG 4

TEMPERATURE DISTRIBUTION IN PIPE IN RUN 49

○ 1 inch from wall of pipe at outside of coil, or top of coil (point 6)
▽ Centre of pipe
× 1 inch from wall of pipe at inside of coil, or bottom of pipe (point 6)

Rate of movement marked with figures and arrow.

point 6, gave useful verification of the progress of the warm oil. By placing these thermocouples near the pipe wall and in the centre it was hoped to detect whether the cold oil passed as a plug, *i.e.* all three thermocouples reacted simultaneously, or whether the warm front penetrated faster at the centre. A typical example is shown in Fig 4. Runs 49, 50, and 52 suggested that the warm oil travelled faster at the side of the pipe next to the central tank of warm oil than at the side away from the tank. Run 61, however, indicated the exact opposite. Run 52, moreover, suggested that the warm oil travelled faster down the centre of the pipe than on either side. In this particular run this may well have been true, as both the flow rate and the pressure distribution indicated that the warm front should have reached the first thermocouples considerably earlier. It is believed that in this instance the flow rate for the first four hours was so slow that the warm oil was cooling in the pipe and in the bottom of the tank near the entrance to the pipe.

It had been hoped that clear evidence would be obtained, either of plug flow or of Newtonian laminar flow with the oil travelling much faster down the centre of the pipe than at the sides. The results are inconclusive. It is considered most probable that the cold oil does move as a plug, at least until it has gathered speed, but that it breaks away from the wall at start-up less sharply than is envisaged by the usual models of plug flow and that some uneven penetration by the following warmer oil can result.

In one of the later large-scale pumping trials a prototype velocity indicator [10] was inserted in the pipe to determine the velocity distribution across the pipe. This instrument was not used in the work described here, as it would take up too large a part of the cross-section of a 4-inch pipe and thus disturb the flow. There is therefore no evidence available to indicate the flow pattern in those runs in which the cold room tank was full of cold oil.

Consider now the problem of whether appreciable loss of structure, and hence of viscosity, occurs in the pipe once steady flow conditions have been established. The average shear stress in each section of the pipe during the periods in each run when steady or near steady flow conditions had been established are set out in Table VI. In addition, overall shear stresses between points 4 and 6, *i.e.* the last 51 feet of observed line, are given. In the field trials it was concluded that the bulk of the shearing appeared to take place in the swing arms, the tank valve, and the first section

TABLE VI

Shear Stress along the Pipe under Steady Flow

Run No	Temp, °F	Oil	Shear stress, dynes/cm² section							Rate of flow, gal/min
			1–2	2–3	3–4	4–5	5–6	4–6	1–6	
42	38	37	550	420	380	470	200	360	410	7·2
43	38		510	430	480	520	340	450	460	7·7
45	36		520	340	390	340	130	260	340	2·7
46	48		150	160	190	130	140	130	150	9·4
51	36		260	310	290	310	210	270	280	3·2
51	36		410	440	350	420	290	360	390	6·6
53	48		130	180	250	190	200	190	190	6·0
54	37		530	470	380	280	370	380	420	5·0
54	37		440	340	300	270	320	290	330	2·6
55	47·5	22	290	150	170	160	130	150	180	5·2
55	47·5		400	360	290	310	200	270	320	15·9
56	36		420	340	310	340	200	280	320	3·6
56	36		460	420	350	390	300	350	390	6·5
57	36		380	240	220	460	290	390	320	2·2
57	36		450	340	270	540	310	450	390	3·8
62	43·5	43	130	100	160	70	—	—	110*	1·4
62	43·5		330	260	380	260	—	—	300*	10·2
63	36		330	280	270	260	—	—	280*	1·8
63	36		400	400	360	350	—	—	380*	3·6

* 1–5, tranducer at point 6 faulty.

of pipeline, since little evidence of breakdown of structure as the oils passed down the rest of the line could be detected. It was hoped that using shear stresses of around 300 dynes/cm² with gelled or near gelled oils at 36° F, evidence of breakdown might have been detected in this rig. The pressure drop per unit length in the first section of the pipe was normally greater than that in the last two sections 4 to 6, but any more definite conclusions cannot be drawn. The probable error of ±0·2 psi is equivalent to an average error of ±50 dynes/cm² in measuring shear stress in any one section of the line, ±10 dynes/cm² over the whole line.

Start-up of Pipe Line and the Constant Shear Stress Viscometer

In one field trial a pipeline was allowed to gel and then pumped under the maximum pressure drop even approximately the pattern of these rates of shear/time of shearing curves, it may reasonably be expected that a shear stress which is insufficient to cause appreciable flow in a pipe in 30 minutes, the practical limit mentioned in an earlier paragraph, might give a small flow rate after several hours (*cf* the curves for 400 dynes/cm² and 290 dynes/cm² in Fig 5). The rate of flow curves in Fig 3 do, in fact, approximate to the shape of these graphs, until about half the capacity of the line has been pumped. After that the flow speeds up rapidly in the line-clearing experiments as the warm oil comes through or becomes steady as fresh cold oil from the cold room tank fills the pipe.

In Figs 5 to 7 the rates of shear, presumed to be equivalent to the flow rates in the pipe, are plotted against time of shearing for Runs 51, 57, and 62, together with constant shear stress viscometer data at those shear stresses nearest to the overall shear stress

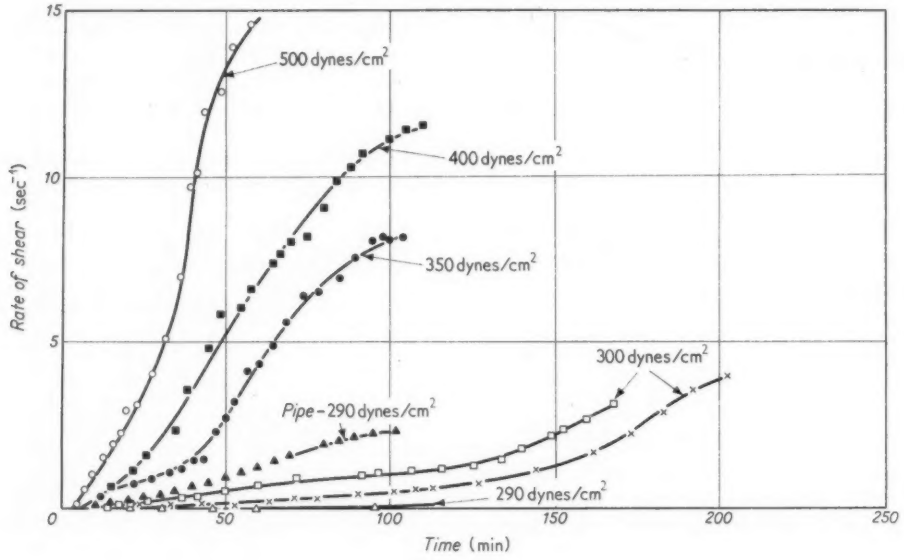

FIG 5

RATE OF SHEAR IN RUN 51 AND CONSTANT SHEAR STRESS VISCOMETERS

available. In spite of the difficulties in arriving at the true flow rate, which were caused by the phenomenon known as " backing up," it was concluded that there was reasonably good agreement between laboratory and pipe viscosities from start-up until the line had been cleared. For the present purpose it is simpler to think in terms of rates of shear in the constant shear stress viscometer and presumed rates of shear in the pipe. The rates of shear obtained using a range of shear stresses are plotted against time of shearing in Fig 5 for Run 51 (oil 37 after 16 days cooling to 36° F).

If the rate of flow in a pipe at start-up does follow at the pipe wall. In two of these the viscometer and pipe give rates of shear at nearly identical shear stresses which were in good agreement until the line capacity had been pumped (Runs 57 and 62). In the other (Run 51) the line pumped at 290 dynes/cm² at a rate comparable with laboratory measurements at about 325 dynes/cm². In Run 54 the oil was too hastily regarded as " unpumpable " at 315 dynes/cm² after little oil had flowed in 145 minutes and a shear stress of 415 dynes/cm² was applied. Examination of the data more critically later showed that some 10 gallons had in fact been pumped in the first 145 minutes and that just before the shear stress was increased the rate

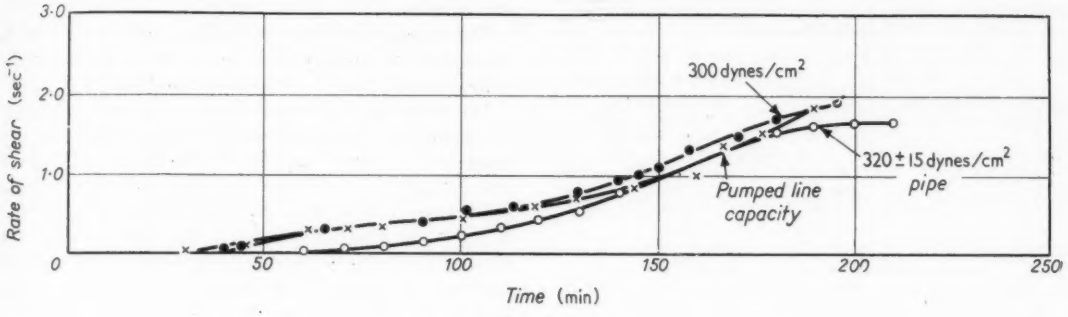

FIG 6

RATE OF SHEAR IN RUN 57 AND CONSTANT SHEAR STRESS VISCOMETERS

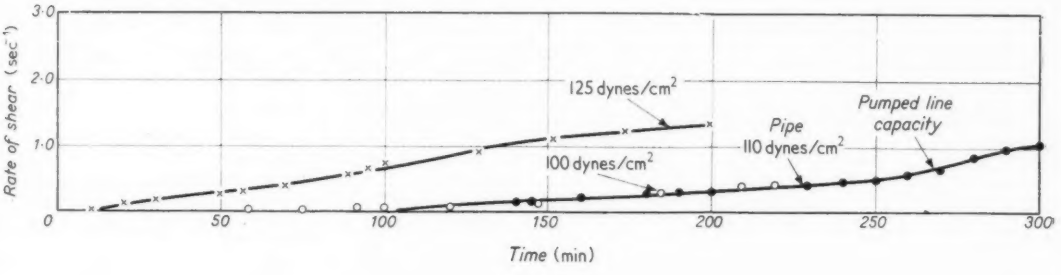

FIG 7

RATE OF SHEAR IN RUN 62 AND CONSTANT SHEAR STRESS VISCOMETERS

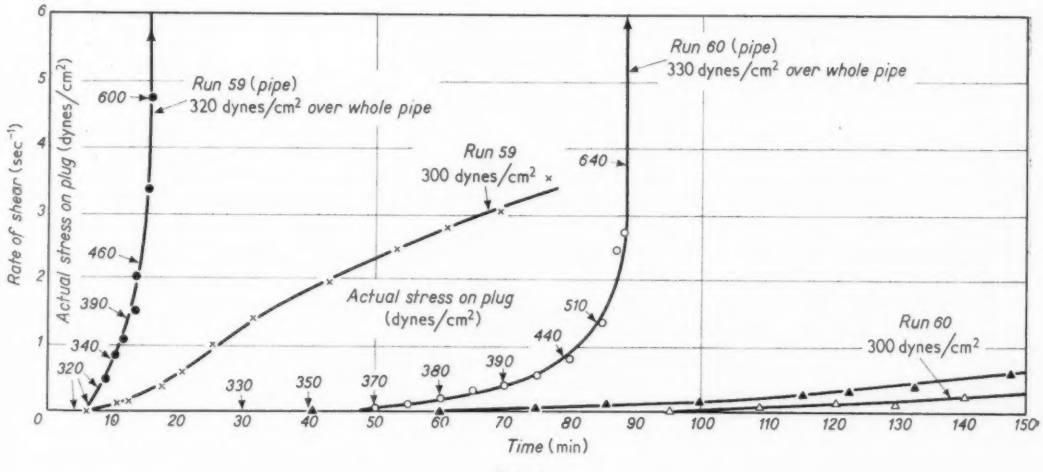

FIG 8

RATE OF SHEAR IN LINE CLEARING RUNS AND CONSTANT SHEAR STRESS VISCOMETERS

TABLE VII

Comparison of Conditions in Pipe and in Constant Shear Stress Viscometer

Run No	Temperature,	Shear stress in pipe dynes/cm²	Shear stress in viscometer which gives same pattern until line is cleared
46	48	145 ± 12	About 150 dynes/cm²
51	36	290 ± 15	About 325 ,,
54	37	315 ± 10 (then 415)	About 280? ,, (then 400) ,,
55	47·5	175 ± 10	About 175 ,,
56	36	315 ± 15	About 330 ,,
57	36	320 ± 15	300 ,,
62	43·5	110 ± 10	100 ,,
63	36	280 ± 10	About 280 ,,

of flow had reached 0·3 gal/min and the rate of shear 0·2 sec^{-1}. It is apparent that the pumping team took an unduly pessimistic view of the prospects, and rapid flow would not have been long delayed at the first shear stress.

The comparison between pipe and viscometer in the runs in which pipe and cold room tank were at the same temperature is summarized in Table VII.

The line-clearing experiments were not normally accompanied by laboratory viscosity measurements. Data are available only for three runs, one of which (48) is unreliable owing to the presence of a marked air leak at point 6, with consequent risk of an air lock in the pipe. In the remaining two (59 and 60), both described in Fig 8, the overall shear stress was 320 and 330 dynes/cm², as against the 300 dynes/cm² aimed at. Measurable flow therefore commenced earlier than would have been predicted by experiments with viscometers under 300 dynes/cm². Thereafter the apparent rate of shear in the pipe increased more rapidly than rate of shear in the viscometer. Calculation of the shear stress exerted on the cold plug

TABLE VIII

Yield Value Data

Run No	Temp, °F	Yield Value Tubes: AFLAC method, dynes/cm²	Yield Value Tubes: Mean	Yield Value Tubes: Constant shear stress, dynes/cm²	Yield Value Tubes: Time to move, min	4-inch diameter pipeline: Applied shear stress, dynes/cm²	4-inch diameter pipeline: Flow rate reached 0·1 gal/min	4-inch diameter pipeline: Flow rate reached 0·5 gal/min
46	48·0	60 90 60	70 70	30 60	Nil in 41 15 : 6 : 7	145	1 min	
47	36·0	200 170 200	190	140 170	30 9; 8	—	—	—
51	36·0	230 200 200	210	110 140 170 200	Nil in 30 29; 33 21; 8 2; 3	290	5 min	25 min
54	37·0	280 340 320 340	320	—	—	315	120 min	—
55	47·5	60 60 60 60	60	—	—	175	1 min	4 min
56	36·0	320 280 280 230	280	170	7; 23	315	15 min	34 min
57	36·0	370 280 340 260	310	170 230 * 260	Nil in 30 28 1	320	70 min	117 min
59	32·5	170 170 120	150	110 90 170	4 18 2	320	3 min	8 min Line clearing
60	32·0	400 380 300 340 340 300 380	350	290 320 340	7 5 3	330	46 min	63 min Line clearing
62	43·5	110 60 90	90	60 90 110	18 1 1	110	80 min	208 min
63	36·0	230 110 140 110 140	150	170 110 60 80	1 2 Nil in 30 25	280	—	60 min

* Increased from 170 dynes/cm² to 230 dynes/cm² in 30-min intervals, in steps of 30 dynes/cm².

of oil in the pipe showed that it was rising as soon as any significant flow occurred and when the flow rate rose rapidly was double the average value over the whole pipe.

Start-up and Yield Value

The constant shear stress viscometer was discussed before the yield value tubes to demonstrate that measurable movement may not commence for some time after a shear stress is applied. The standard yield value technique developed by Gill and Russell [6] and adopted by AFLAC [7] subjects oil in a narrow bore yield value tube to shear stresses which increase by 28 dynes/cm² every five minutes until flow is observed. This may therefore be expected to give results higher than the true yield value. Gill and Russell suggested that when flow ultimately commenced in a gelled pipe under shear stresses less than the apparent yield value, autogenous gel destruction was taking place. They considered that air bubbles and discontinuities in the gel caused sections nearest the pump to be subjected to higher than average shear stresses and that the gel yielded in sections. This may well occur in some cases, but it is equally likely that yielding at low stresses after long delay is merely a manifestation of the time-dependent properties of the gel.

The yield value data obtained by the Panel's method is set out in Table VIII, together with a limited amount of data obtained by applying a constant shear stress to the yield value tubes. This, however, is sufficient to demonstrate that constant stress will give a lower yield value than increasing the stress every five minutes. The pipeline was used with constant applied stress, since the prime requirement was the time likely to elapse before adequate flow commenced at selected shear stresses. Yield value data is therefore not available from the pumping runs. It does, however, appear that the AFLAC yield value procedure will frequently indicate whether appreciable flow can be expected in 30 minutes to an hour.

Steady Flow Conditions and the Constant Rate of Shear Viscometer

The early large-scale pumping trials were interpreted in terms of equilibrium viscosity at the rate of shear presumed to occur in the pipe. This equilibrium state was reached after shearing for an hour or more in the viscometer, and the trial conditions were such that the mean residence time of the oil in the pipe was normally of the same order. The later large-scale trials not only involved long residence times but also much higher rates of shear. The concept of equilibrium viscosity was still adequate. In the present rig, residence times were normally less than 20 minutes once steady flow had been established, and the oil was colder than the great majority of the oils pumped on the large scale.

It has been shown above that under steady flow conditions shear stresses, and hence pipe viscosities in the first section of pipe, probably exceeded those in the last two sections. It is therefore reasonable to anticipate that equilibrium viscosities would be less than apparent pipe viscosities, since the former are normally determined after an hour or more of shearing

TABLE IX

Pipe Viscosities under Steady Flow Conditions compared with Laboratory Viscosities

Run No	Temp, °F	Oil	Conditions at steady flow			Viscosities determined in coaxial cylinder viscometer					
			Rate of shear, sec⁻¹	Residence time, min	Pipe viscosity, poise	At ½ residence time		At residence time		"Equilibrium"	
						Oil in beakers	Oil in tank	Oil in beakers	Oil in tank	Oil in beakers	Oil in tank
46	48	37	6·9	7	21	23	—	20	—	14	—
46	48		About 26	2	About 11	13	—	12	—	10	—
51	36		2·4	23	120	120	—	105	—	75	—
51	36		4·9	11	79	95	—	79	—	50	—
53	48		4·4	12	43	—	50	—	44	—	33
54	37		3·7	15	111	115	95	96	82	56	
54	37		1·9	30	171	180	150	140	125	100	
55	47·5	22	3·9	14	45	42		39		30	
55	47·5		11·8	4½	27	28		25		20	
56	36		2·9	18	110	160	86	135	70	85	60
56	36		4·8	11	81	115	75	100	65	62	48
57	36		1·65	33	194	190		160		120	
57	36		2·8	19	141	125		110		75	
62	43·5	43	1·04	50	111	About 180	82	About 150	75	—	65
62	43·5		7·7	7	40	46	34	44	30	32	25
63	36·0		1·3	40	216	270	225	225	195	200	170
63	36·0		2·7	19	142	150	135	130	120	95	85

in the viscometer. The results of the early runs confirmed this view.

The pipe viscosities under steady flow conditions are compared with laboratory viscosities in Table IX, at three different levels; (*a*) after a time of shearing equal to half the mean residence time of the oil in the pipe, (*b*) after a time of shearing equal to the mean residence time, and (*c*) at equilibrium viscosities as employed in the large-scale field trials. This equilibrium viscosity level is invariably less than the apparent pipe viscosity.

The laboratory viscosities were obtained partly on oil stored in steel beakers of a comparable diameter to that of the pipe and partly on samples taken from the cold room tank. In the earlier runs few samples were taken from the cold room tank, as it was feared that sampling a tank of this size would disturb a large proportion of the oil. This was overcome by hanging steel beakers at various levels in the oil and examining the oil in them after the pumping run. In this way samples were obtained with the minimum amount of shearing, the viscometer cylinders inserted, and the viscosity measurements made on the following day.

In some runs, notably No 57 on oil 22 after seven weeks at 36° F, the beakers stored in the cold room and the samples taken from the tank had identical viscosities. In others, Runs 54, 55, and 63, the differences between the two were about 15 per cent of the larger, *i.e.* that on the oil in the "floor beakers." Only in Runs 56 and 62 was a large difference detected. The former relates to oil 22 after three weeks at 36° F. This oil came to a substantially higher viscosity level after storage for seven weeks at 36° F (Run 57). The second relates to oil which had only been at the test temperature for five days after slow cooling from 52° to 43·5° F. It was not anticipated that the oil in the tank would have reached the viscosity level of the oil in the "floor beakers" after so short a time at the test temperature.

In spite of these variations, it is possible to see a clear pattern, and it is considered that the pipe viscosity is in good agreement with laboratory viscosities after shearing for half the mean residence time of the oil in the pipe. Calculation of viscosity at the mean residence time gives a rather lower level for the laboratory viscosities.

CONCLUSIONS

In addition to information as to how selected oils will pump under prescribed conditions the rig has shown:

(*a*) That the increase in flow rate on starting up with the pipe full of cold oil is very similar to the increase in rate of shear when the oil is sheared in a coaxial cylinder viscometer at the constant shear stress applied to the pipe.

(*b*) The yield values obtained in narrow bore yield value tubes subjected to a shear stress which is increased by about 30 dynes/cm^2 every five minutes have in general given an indication of whether the line could be started up in about an hour.

(*c*) That once steady flow conditions have been established there is some evidence that the shear stresses, and hence viscosity, in the first section of the line are greater than those in the last two sections.

(*d*) That pipe viscosities after steady flow has been established are comparable with laboratory viscosities as determined in a coaxial cylinder viscometer at the rate of shear presumed to exist in the pipe. If the laboratory viscosities are taken after a time of shearing equal to half the mean residence time of the oil in the pipe, pipe and laboratory viscosities are in good agreement.

ACKNOWLEDGMENTS

The authors are indebted for permission to publish this paper to the Board of Admiralty, who are not, however, responsible for the opinions expressed. The original design for the rig was proposed by members of the Admiralty Fuel and Lubricants Advisory Committee, the actual construction being the responsibility of A. J. S. Baker, then on the staff of the Admiralty Oil Laboratory. It has been operated with the assistance of the authors' colleagues, especially C. J. Spilman and M. J. Willis, who have been regular members of the Admiralty Oil Laboratory trials team.

References

Davenport, T. C., and Russell, R. J. "The Full-Scale Pumping of Admiralty Fuel Oil and its Relation to Laboratory Tests," this symposium.

[2] Bingham, E. C., and Green, H. *Proc. Amer. Soc. Test. Mat.*, 1919, **19** (11), 641.

[3] Buckingham, E. *Proc. Amer. Soc. Test. Mat.*, 1921, **21** (11), 1154.

[4] "The Measurement of Flow Properties by Coaxial Cylinder Viscometer," this symposium.

[5] Paper accepted for publication by Physical Society, still in press.

[6] Gill, F., and Russell, R. J. *Industr. Engng Chem.*, 1954, **46**, 1264.

[7] Russell, R. J. "The Yield Value of Admiralty Fuel Oil," this symposium.

[8] Private communication.

[9] Wyllie, D., and Taylor, W. E. L. "The Practical Conditions of the Storage of Admiralty Fuel Oils," this symposium.

[10] Baker, A. J. S., Tourret, R., and Jones, J. T. *Engineering*, 1959, **187** (4845), 82.

DISCUSSION

The Chairman: That brings us to the discussion. We are fortunate in having with us this afternoon, Dr A. C. Monkhouse, who was the chairman for many years of both the Fuels Sub-Committee and Panel F, whose work we have been discussing. It is a great pleasure to ask him to open the discussion.

Dr A. C. Monkhouse: I would like to stress what our chairman said, how much the oil industry has helped in the work of Panel F on pumpability. Without their help, the Panel would never have succeeded in making the advances it has. It is a very difficult problem. One thinks of it as a physical problem, but as Professor Sellers has mentioned, it is a chemical problem too, and if we perhaps knew a little more of the chemistry, we should be able to understand more of the physical aspects. The two main difficulties were, first, the problem of knowing what was taking place during pumping at the storage installations, and secondly, the finding of some physical property which would give a measure of pumpability of oil after it had been subjected to pre-treatment to simulate what is taking place at a low temperature. Therefore, the work which Mr Davenport has described, of full-scale trials, gave a great lead to the laboratory work.

One problem is that we are dealing with oils coming from various parts of the world, and therefore it is going to be difficult to devise a test which is applicable to all oils. I do, however, feel that the work that has been done so far gives a greater chance of ensuring that the oils on storage would behave satisfactorily. Much more is known of the physical properties of oils since Panel F started its work, and in that respect I think we ought to congratulate its members on their work.

G. C. Ackroyd (DSIR, Fuel Research Station, Warren Spring Laboratory): I would like to make two points on the paper by Mr Davenport. First, he gives the impression that when an oil is being pumped through a pipeline, the viscosity of the oil, once it is moving down the line, is more or less constant. In one of our later trials we went to the extent not only of instrumenting with mercury gauges and pressure transducers, but even instrumenting the first 25, or 50, feet of the pipeline with differential water-gauges. I think if these data are analysed we find that viscosity breakdown occurs along the pipeline, and this simulates what happens when an oil is sheared in a co-axial cylinder viscometer.

The next point was that Mr Davenport showed one very good picture of instrumentation, and I thought he was going to explain what the "elephant's trunk" was, with a valve on the end. He did show us that if there is no air in the line, between 1·7 and 2·5 times the amount of oil can be got through the pipe than is the case when the line contains air. This is a very important point, for it should enable the diameter of the pipeline to be considerably reduced. In our pumping trials we actually put air bleeds on every high spot on the pipeline, as shown by the height survey, and these were the "elephants' trunks," actually a ½-in valve on the pipeline with a length of rubber tube attached. We did find, to our cost, that we had to have the rubber tubes to lead away the oil, otherwise most of the surrounding areas got painted with oil.

T. C. Davenport (British Petroleum Co. Ltd): In principle I would agree with Mr Ackroyd. During the steady state pumping trials the breakdown in viscosity to be expected along the line was relatively small and was masked by the presence of air (which gave rise to high viscosities in certain sections of the pipeline) and by the temperature drop down the line, which increased the viscosity and thus masked any effect due to breakdown.

However, even when these effects are taken into consideration it would appear, as illustrated in Table IV, that there is an observable breakdown in viscosity as the oil travelled down the line, and this was shown to correlate approximately with the breakdown which occurred in a co-axial cylinder viscometer after shearing for the same length of time.

The start-up trials showed (Fig 9) quite clearly that there was a very marked breakdown in viscosity from about 10,000 to 300 poise as the oil yielded and moved slowly down the test line.

Dr D. Wyllie (Admiralty Oil Laboratory): I would like to comment on the paper on the full-scale pumping trials presented by Mr Davenport.

The authors have developed a most interesting method for the calculation of probable velocity distribution in the pipe from temperature traverses, and in Table VI demonstrate that this results in remarkably good agreement between the pipe viscosities obtained in the co-operative pumping trials and laboratory viscosities.

McAdams ("Heat Transmission," 3rd Edition, McGraw-Hill, New York, 1954) has suggested that when in laminar flow there is a temperature gradient across a pipe the fluid properties should be evaluated at the temperature

$$tf = \tfrac{3}{4}\, tb + \tfrac{1}{4}\, tw$$

where tb = bulk temperature;
tw = wall temperature.

This makes no attempt to derive the velocity distribution across the pipe, but nevertheless it was of interest to see how it would work out when applied to the results of the series of co-operative pumping trials dealt with in Tables II and VI of the paper. For this purpose I have taken the long straight length of pipe at the end of the test line which the oils did not reach until they had already suffered substantial shearing and which did not contain obstructions or air locks. From the same agreed data as that used by the authors we obtain:

Oil	tf, ° F	Laboratory viscosity, poise	Pipe viscosity, poise
A (1)	34·5	24	22
B (37)	47	25	26
C (30)	41·5	16	20
D (35)	40·5	65	80
E (12)	45·25	80	71
G (19)	43·75	20	21

According to Metzner, Vaughn has stated that this method of calculation gives insufficient weight to the wall temperature; nevertheless, it appears to be useful when we do not have appreciable gelation occurring at the pipe wall. It was not adequate with oil F (40), since this oil showed marked signs of gelation at the pipe wall in the winter pumping trials.

Dr R. J. Russell (British Petroleum Co. Ltd): I would like to amplify Dr Wyllie's remarks. The calculation given in the Appendix to obtain viscosity at a constant temperature was made because the McAdams formula was empirically developed using test conditions where the viscosity differences were only small. Since we were

trying to obtain viscosities to compare with the laboratory viscosity measurements, in the hope of getting a one-to-one agreement, the use of such an empirical formula did not appear admissible.

Professor E. S. Sellers: I gather that this particular problem of fuel oil and fuel oil pumping has been the rheologist's graveyard, and somebody told me that Dr A. E. Dunstan first started this work in 1915. When I became concerned with it, it seemed to me that one should know exactly what was going to happen in the pipeline. When oil of this sort had a definite yield point it should yield adjacent to the wall, and the middle section would then go forward as a plug. With suitable instrumentation it should be easy to confirm that. The trouble is that when the instrumentation was fitted, it was another example of a splendid theory being spoiled by experiment, because no matter how we tried, we could never show that the oil would, in fact, go forward as a plug. Sometimes it seemed to go in one half of the pipe, and not the other. The reason why I mention this now is because from time to time people have referred to the " pipe viscosity," and it has not been made clear so far what that means. If we assume the oil has Newtonian characteristics, and flows with a fully developed parabolic velocity profile, then the pressure drop along a certain length of the pipe corresponds to a certain viscosity. That is " pipe viscosity."

So far as the flow patterns in pipelines are concerned, they have occupied us for a very long time. There was, for instance (it is not reported in this symposium), quite a lot of work done at the Admiralty Oil Laboratory in trying to obtain velocity distributions across pipelines, in smooth pipes, steel pipes, glass tubes, under all sorts of conditions. Some of this, I think, Dr Russell may be commenting on in his work on yield point, but I certainly cannot promise that we shall make the whole business clear, because we still do not know for sure what happens in big pipes.

Captain W. R. Stuart (Admiralty): Following up what Professor Sellers and Dr Wyllie have said, the latter suggested that with laminar flow one might possibly use some of McAdams' recommendations for the temperature at which to take fluid properties. I wonder whether, in fact, we get anything like any sort of laminar flow at all when you have some " structure " in the fluid in a pipe. I do not know whether the Panel have looked into that. Whether, if you have a structure moving along a pipe, you have something more like seaweed tumbling over and over, as water flows in a channel in the docks, rather than anything that can be thought of as a regular mathematically expressible movement.

The other thing I would like to ask is in relation to Mr Davenport's paper. I was very interested in the big blockage to flow caused when air gets into the pipe, giving up to something like 50 per cent less flow. Could Mr Davenport advance any theories as to why the air causes this big reduction in flow?

T. C. Davenport: There is no entirely satisfactory theory to explain the large reduction in flow rate caused by the presence of air in a pipeline. One of the simplest explanations is that the volume of air present reduces the effective diameter of the pipe, and hence gives rise to much larger pressure drops than would occur if the pipe were flowing full. It has been shown (*Oil Gas J.*, 26.7.54, **53** (12), 185) that there are seven types of flow which can occur when a liquid and gas are being pumped together. In the cases where there is a free surface there can be large friction losses due to wave formation. However, at the low Reynolds numbers found in these trials I think a simple reduction in effective pipe diameter is the most likely explanation.

In all the tests, with the exception of the pumping from underground storage, suction lines were investigated where, due to expansion, the effect of air was very pronounced. The same problem can, however, occur in delivery lines, although a greater mass of air is needed to give the same effective reduction in pipeline volume.

Captain W. R. Stewart: Does that imply that the air bubbles stay put, if you have the pipe partially air locked?

T. C. Davenport: It was quite definite that air was not cleared from the line when pumping was taking place. Rather the reverse, since at the end of every run large quantities of air could be vented even though the lines were vented clear of air at the start of each run. It was also found, in addition to accumulating at high points, that contrary to expectation air accumulated at a low point where the pipeline passed under a railway. No satisfactory hypothesis has been put forward to account for this behaviour or to explain where the air came from during each test run.

G. A. Vickers (Esso Petroleum Co. Ltd): Was the test rig on the suction side? [Yes.] What sort of pumps were used? Were they pulsating reciprocating pumps? [They were.] Then there would be air expansion in the suction line on each stroke of the pump. The air is expanded, then contracted and there is certainly a loss of capacity.

T. C. Davenport: The suggestion that there were pressure surges in the line due to the action of the pump was not borne out in practice. Two factors would account for this. First, the pumps were of the three-throw reciprocating type which give a fairly constant suction head. Secondly, there was a large surge reservoir of about 1800 gallons capacity to eliminate any surges in the suction line itself.

If the line were completely filled with oil a pressure surge should be transmitted with the speed of sound along the line in the oil. In fact, on many occasions when the pump was stopped it was an hour or two hours before the tank pressure was transmitted along the line to the pump. This was probably accounted for by the presence of air in the line rapidly damping down any pressure surges.

Captain L. E. S. H. Le Bailly, O.B.E., R.N. (Admiralty): I seem to remember the Admiralty Oil Quality Committee once writing to the Admiralty and saying, I think, that " they had never seen so much human ingenuity devoted to creating the most difficult possible system for transferring oil from one entirely unsuitable receptacle to another." I would like to ask the Admiralty Department concerned whether anything has now been done to clear up this complicated pipe system.

Commander H. D. Nixon (Admiralty): I do not belong to the section of the Admiralty that actually designs the pipeline, but I do not believe there has been any vast improvement since Captain Le Bailly's days. Some attempt is being made to predict the flow of oil from the odd type of receptacle to the receiving end, but even so, I understand that the calculations are not very accurate. But that is all I can say.

Dr C. M. Cawley: Has the Admiralty obtained any help from the practical experience of other users of these oils? I know, of course, that the industry has given a tremendous amount of help in studying the Admiralty's

problems, but I am not asking that; I am asking, has the Admiralty obtained any help from the experience of other users, or is in fact this problem confined to Admiralty conditions of storage and use?

Captain W. R. Stewart: I do not think our problems are quite so bad as suggested. We have pretty normal pipelines, and I am surprised to learn that the Oil Quality Committee did in fact say this. I do not think our pipelines are greatly different to those in merchant ships generally. I am well aware that our problems are peculiar as regards the conditions under which we want to pump oil. That is, in certain cases, from unheated tanks, and so forth; and on having to allow for conditions where steam is not available, so that it is impossible to heat the tank and we have to pump cold oil. But I will certainly look into the matter to see whether there is anything in the suggestion that our pipelines are so odd that they make this problem so much more difficult.

Dr C. M. Cawley: Would you therefore say, Captain Stewart, that no other user has quite the same problems as the Admiralty, and that there is in consequence no experience on which you could draw from other sources?

Captain W. R. Stewart: I see your point, Mr Chairman. It is not so much that our pipe systems were odd, but that the pumping conditions were. I have not heard of any other user having quite the same problems. I do not know of any shipping companies interested in our work at the Admiralty, apart from the tanker people. I do not know what happens in the whalers, but I imagine they use plenty of tank heating. It would be interesting to know of their methods. They are the only people I can think of who operate in the Arctic all the time.

Captain Le Bailly: Since everyone is casting doubt on my veracity, I would remind you, Mr Chairman, that after you and I had spent nearly two hours watching an oil fuel filling funnel on H.M.S. *Vanguard*, hoping for some oil to arrive, a lot of water came over.

T. C. Davenport: A previous speaker stated that shearing stresses and flow rates in ships' installations could not be calculated accurately because of the large number of bends, valves, and other obstructions to flow. Although this is undoubtedly true to a large extent, I think it should be emphasized that in the tanker pumping trials, in spite of difficulties in measurement due to the pitch and roll of the ship, and the effect of the ship's trim, excellent agreement was obtained (Fig 5) between the pipe viscosity and the viscosity measured with a Ferranti viscometer.

N. S. Rae (Esso Research Ltd): I recall that, when I was on the Fuel Flow Panel in about 1953, one of the biggest puzzles we had in connexion with relating the results of our work to practice was that of obtaining a realistic sample from the field, and then obtaining the data on that sample unchanged. We have heard about the techniques used in getting a sample from the field to the laboratory, and then carrying out the determinations at the temperature at which the sample was taken originally.

What I am troubled about, though, is how the transfer was made from the sample container to the measuring instrument without disturbing the structure. I have noted the close agreement between the laboratory results and the calculated results from the field, but wonder whether this is almost coincidental, in view of this other difficulty I have just pointed out. Would any of the authors like to comment?

Dr D. Wyllie: We have been well aware of this possibility. It is virtually impossible to avoid loss of some structure in transfer of samples from a tank, and I would like to point cut that in the work with the laboratory pumping rig we were most careful to leave samples in beakers and to fill viscometers and leave them under the same conditions, same kind of storage, same rate of cooling, as the oil that was being pumped. From these, and from samples that were actually fished out of the tank at the end of a pumping experiment, it appeared that although there was some loss of structure in sampling, it was not catastrophic if we used proper sampling apparatus. There was one attempt to measure viscosity *in situ* in a tank. Mr Ackroyd designed a special type of viscometer which could be operated in the tank, and gave adequate results, provided it was not operated too near to the yield value of the oil. This was used in one of the major trials.

I would like to recall that there was also an attempt to get the velocity profile other than by estimations from pressure drops and temperatures. Mr Baker and Mr Tourret, who are no longer in Admiralty service, and Mr Jones, who is still at the Admiralty Oil Laboratory, evolved a velocity meter which was used in one of the later field trials; it had not been devised at the time of the earlier ones. Although the results were affected by the viscosity of the oil, it gave a useful indication of the general velocity pattern across the pipe. We did not use it in the laboratory pumping rig, as it would have constituted a substantial obstruction to flow in a pipe of only 4 inches diameter.

E. J. Widdowson (Admiralty Oil Laboratory): As one of those who has to evaluate the experimental work before it is reported to my Lords of the Admiralty and long before it is reported to the IP, I myself am rather worried about the particular point that Mr Rae raised, because it is perfectly obvious one cannot insert any sort of conicylindrical viscometer into the middle of a 90-foot tank and measure viscosity under those particular conditions without any disturbance of the structure. Some transfer is involved, even to do the tests on the site, and I have had some doubts as to whether the "on site" figures really do represent the true values in the middle of the tank. I must say that none of the discussions I have had with my own staff, or with any members of the Panel, have completely convinced me that we have got absolutely correct figures. Dr Wyllie mentioned that, in the rig trials, we did attempt to tackle this by taking the Ferranti viscometer into the cold chamber, putting the oil in it, and leaving it. What he did not say, although it was mentioned in the paper, was that this was done for only one or two days. The Ferranti viscometer would not stand up to being in the cold room for three weeks or more. It just did not like working after that length of time, and the results were unreliable, owing to "stickiness" of the motor and transmission.

However, I feel that the Ferranti work in the cold chamber, even for one or two days, has at least gone some way to meet Mr Rae's points. It has confirmed that, under those conditions, the results are not too bad, and there is a fair degree of probability that the depot results are also sound. But I would like to see someone conceive a miraculous new way to measure tank viscosities *in situ*. Mr Ackroyd has had one or two shots at this, on the surface, but I would like to think of some way that one could do it in the middle of the tank without

fetching the oil out, without even shearing it by forcing it into a viscometer or sample pot, which in itself must do something to the structure.

G. C. Ackroyd: I fear Mr Widdowson has rather the wrong impression of the instrument. It was built exactly for that purpose—to measure the viscosity of the oil *in situ* in the tank, anywhere from the top of the oil right down to the layer in the bottom, 20 or even 30 feet below. This was done by means of drain rods. The instrument consisted of a cylinder, about 1 foot long and 2 inches diameter, electrically driven at a constant shearing stress. A description has been published. This instrument was lowered on the end of drain rods into the tank and the motor switched on. The rate of rotation was signalled to the surface electrically, and I remember, one night, in the depth of winter, three or four people at one of the Admiralty oil depots in the north sitting on a mossy bank, watching a red light flashing right on the top of the tank, 30 feet high, which indicated that the cylinder was rotating once in every five minutes, and in between whiles we would go up on top of the tank to see whether the thing was really working; we could not believe it. And this is the point: this instrument did show enormously high viscosities, higher viscosities than we have ever been able to determine by taking the sample out of the tank, and bringing it to viscometers. In general, the viscosity data obtained using this viscometer correlated very well with the pipe viscosities calculated from the pressure loss when the same oil was pumped down at 14-inch or 18-inch pipeline.

T. C. Davenport: In answer to Mr Rae's question I would like to point out that the miraculous agreement between large-scale and laboratory viscosities was only obtained for equilibrium viscosities, *i.e.* when the oil had been completely sheared both in the pipeline and in the viscometer. Fig 11 shows that when the complete breakdown curve is considered, the agreement is not so good. As would be expected, the laboratory breakdown curve is lower than the full-scale curve, indicating that a certain amount of breakdown has occurred during sampling and while loading into the viscometer.

Dr D. Wyllie: It is correct that in work with the pumping rig the Ferranti viscometers could not be taken into the cold room earlier than two or three days before they were used, but with the constant shear stress viscometers, which are much tougher, we could leave the cylinders filled with oil for the full time the oil was in the cold room and connect the driving system when it was desired to make measurements. I agree with Mr Davenport that probably the reason why the graph of pipe viscosity against time at the start-up of the gelled line is higher than the viscosity of samples in a viscometer is that in field trials work was done on the oil, getting it out of the tank and into the viscometer. We succeeded in work at the pumping rig in getting better agreement between pipe viscosity and laboratory viscosity curves on starting up a gelled line, since we were able to leave viscometers filled with oil alongside the pipe in the cold room while the pipe was conditioning at the test temperature.

Captain L. E. S. H. Le Bailly: I have just heard a comment from somewhere at the back saying, "What's all this work in aid of?" I would like to say that, between the wars, Admiralty boiler fuel was a low viscosity high grade fuel requiring a large quantity of middle distillate diluent. The Royal Navy was one of the largest buyers in the world, and supply of this high grade fuel was easily able to meet the demand. Indeed, the assured supply of a high quality fuel for the Royal Navy, by the development of the Middle East oilfields, was a settled policy.

In 1948 the two main sources of supply of furnace fuel oil were:

(i) the Western Hemisphere, on which for strategic reasons, the Navy would rely in time of war;
(ii) the Middle East, from which, for economic reasons, it was desirable to stockpile in time of peace.

The increasing use of the internal combustion engine and the jet engine, the existence of a dollar shortage, and a world shortage of oil had entirely changed the supply situation, and it was then an economic necessity to obtain the maximum quantity of saleable products from each barrel of crude extracted from the earth. "He who pays the piper calls the tune," and insistence by the Navy on a supply of fuel oil to pre-war standards at the expense of a shortage of gasoline and other saleable and profitable products could neither be practicable nor possible.

It was then almost fifty years since liquid fuel had been introduced into the Navy. Forty years before, the Admiralty Oil Committee, amongst whom were numbered Lord Fisher, Sir Henry Oran (the Engineer-in-Chief), Sir Boverton Redwood, Dr G. T. Beilby, and Arnold Philip (the Admiralty Chemist), had issued the first specification.

It had been recognized that one of the main advantages derived from the use of oil instead of coal was the ease with which it could be stowed in remote parts of the ship and pumped from place to place when required. A large amount of thought and research had been devoted to this aspect, and the final specification ensured that the oil supplied to the Navy would be pumpable at all temperatures likely to be encountered on board ship. Through the years it had been found possible to relax on other aspects of the specification, but never on this particular requirement until, in the days after Dunkirk, the shortage of middle distillates first began to be felt. But even then, and subsequently in the blackest days of the war, this requirement was maintained, though to a modified degree. In 1948 this was no longer so, and the specification issued by the Admiralty contained no guarantee that the Navy's oil would be pumpable with existing equipment at normal temperatures. Indeed, we were hardly even equipped technically to explain our difficulties to the industry.

You mentioned Lord Geddes and Professor Garner, Mr Chairman, but you did not mention your own contribution towards helping us, and I think I can reveal now perhaps that the ideas of the committee occurred, as perhaps all good ideas should occur, after an Institute of Petroleum dinner. The three men who really encouraged us to start this Committee—I see two of them here, Charles Hill and Cyril Martin, and I expect Frank Jones is somewhere about—were the three who really took us in hand, looked at our difficulties, and encouraged us to really get going and approach the industry and ask them for help. It was, I think, your assistance, Mr Chairman, and Professor Garner's assistance, and Lord Geddes' encouragement, that made the Admiralty realize that the help was there for the asking, and that we had only to come forward and ask. What we have heard to-day is a most remarkable culmination of ten years' effort, on a great many people's part. I would say that the Fleet now is a thousand times better equipped to operate anywhere in the world than it was at the end of the war.

C. V. Hill: Could I give an alternative version? I think we have forgotten a very able and far-seeing

officer called Frank Mason, who used his not inconsiderable charm to persuade the oil companies to do all the work the Admiralty wanted, at the oil companies' expense.

I really do think that in the last ten years an enormous amount of very difficult work has been done. If you compare the knowledge that you fellows have now with that with which you started off in 1949, I think you have come a very, very long way. I am most interested to see that you have decided on a temperature of 48°, but I am not quite clear whether that is due to the fact that the ships' suction lines go through the crews' quarters, which are air conditioned at about 70°, or whether it is due to the fact that the storage tanks have been shown to have this insulating shell of gel, which gives you warm oil in the middle. Perhaps somebody could tell me just exactly what the basis is for this figure of 48°, which sounds to me a very reasonable one.

But there is one other point, if I may just mention it now, and that is Dr Wyllie's remarks about the oil companies' viscosity curves, which I think a little harsh, really. Not now belonging to an oil company, perhaps I am the right person to say this, but to my knowledge at least three oil companies put out these curves, and two of them, I know, are identical. The companies sell the oil to a customer who is not going to put it away for 20 years in case a war happens. They put it straight into the ship for him, and he uses it there and then. They tell him the viscosity of the oil as delivered, then he looks at his graph and says, " Well, now, for good atomization I want a viscosity of so many seconds, therefore I must heat it to such and such a temperature," which he proceeds to do, and it is nearly always a pretty high temperature. So the question of structure just does not arise at all.

I think perhaps Dr Wyllie has misunderstood the purpose of these oil companies' graphs.

I congratulate the people on the way they have been working the pumping rig. We used to call it " the simulated Arctic trials rig," and it is, of course, intended to be a ship's fuel system. I hope it is going to be applied largely to ships' work, because I have been satisfied for a long time that the shore problem is really solved, as soon as you put steam in everywhere to heat the oil. The insulation manager can always get out of his trouble that way. But you can get into trouble on ships, because of war damage and emergency matters, and I think that is really the thing to concentrate on, ship work.

Dr D. Wyllie: I would like to assure Mr Hill that we do appreciate the purpose of these viscosity calculators. They, however, gave us a very useful reference line for oil with little or no " structure."

Professor E. S. Sellers: Without recounting the whole history of this, perhaps I may be allowed to say that Panel F has never been distinguished for unanimity of opinion. A comment was passed, " Is there really a problem at all?" Just occasionally, I think, Panel F used to stop in their deliberations and say, " What are we trying to do?" We know to some extent what we are trying to do. We know that this work was first suggested by the fact that some oil would not flow when it was wanted to flow. It was known that these oils developed " structure," which would break down if it could be sheared, and the idea took hold that once you could get the oil to move at all it would continue to move. And so we got this idea of an equilibrium viscosity, as a focus of our attention in order to predict the actual flow, not the transient viscosity during the early stages when flow was beginning, but the viscosity which applied when the oil was flowing steadily.

At one stage in the attempt at producing a specification it was thought that if the oil could be made to start flowing it would continue to flow. It seemed logical that the specification test should require the yield point. Dr Russell will tell you of some of the work that went into that. But in the end we had to come down to a viscosity specification. With the oils that we have we know that the term " viscosity " should really be written in inverted commas. We have to go back to the real definition of viscosity, that it is just a shear stress divided by rate of shear. But shear stress and rate of shear can only be defined in terms of the actual equipment employed. And so, in attempting to bring up specification figures, every class of every ship in the Fleet was looked at and measured—the suction pipes were measured, the bends were looked at, every shore installation was examined, length of pipe, size of pipe, bends—and for every one, this formula $\triangle PR/2L$ was worked out. And so we could tell, with the pumps and the pressure drop which was available, what the shear stress per unit area was for every class of ship in the Fleet, and for every installation.

Obviously, any specification must take account of the worst possible conditions, and so a corresponding value of the shear stress per unit area was adopted for specification purposes, so that viscosities could be calculated or measured under that particular value of shear stress. The viscosities would then be meaningful in terms of the actual equipment in which the oil would be used. We knew that a certain class of ship, under full steaming conditions, required a certain amount of oil. This had to be considered in relation to the pipework, the tanks, the pumps available, and the suction heads. All this was then translated into a viscosity figure for specification purposes. The only thing left was temperature, and that was selected finally by the Engineer-in-Chief of Fleet's Department on the basis of considering what temperatures would normally be available; that is why this figure of 48° came up, and in the end it was decided to specify a viscosity corresponding to a desired pumpability for full steaming at 48° F, together with a subsidiary test at a lower temperature which would represent a smaller flow rate under conditions where a ship might be laid up in the cold weather without heating, or under damage conditions, where long sections of suction pipe might be actually immersed in cold sea water, with the result that the oil temperature might be low. As a result of a practical survey of this kind, the Admiralty were able to select a shear stress per unit area condition and a temperature condition under which they could define a viscosity requirement which could be translated straight away into the fuel consumption under steaming conditions of the worst class of ship in which the fuel would be used.

G. C. Ackroyd: There is another point—we have seen that in underground storage the temperature varies between 48° and 54° F, and to some extent the choice of 48° F for the test temperature must be associated with this.

Commander H. D. Nixon: I agree with Mr Ackroyd as much as I agree with Professor Sellers, but the temperature requirement really had to be tied to pumpability requirements in shore storage and in ships. As Mr Ackroyd so rightly says, in underground storage, within a degree or so, the oil temperature is about 48°, and one had also to choose a temperature which would suit ships as well. One reckoned that with sea water temperatures of about 40° to 45° the oil temperatures in the tanks would probably be about 48°, because of the internal heat in the ship; and that seemed a happy choice of tem-

perature, particularly when one was thinking about the areas of the seas which the ships would traverse. Looking at the thermal charts of the oceans and at what I think are called isochrymes, which are the cold temperature lines, it does give an astonishing usage of the sea even at the coldest time of the year, if you choose 48° for your fuel temperature, corresponding to 40° or 45° for your sea temperature. And so that corresponding with the underground storage temperature at 48° was decided upon, since it was desirable to have a specification test temperature which satisfied both requirements.

Dr D. Wyllie: Mr Davenport mentioned a figure of 25 poise as a typical requirement for Admiralty installations. The actual figure will vary according to the type of installation. We have been thinking of a level a bit lower than 25 poise. The final figure decided on for specification purposes will be announced in due course.

S. D. Cooper (Shell International Petroleum Co. Ltd): I have been a member of AFLAC for only roughly the last five years, and consequently I have known of the objective of Panel F during that time. I think Professor Sellers summed it up very neatly when he said that it was to make sure that an oil, after an undefined period of storage, remains pumpable.

What I have never been quite clear about, though, is what really started this work. Captain Le Bailly mentioned that the Navy was in serious trouble. How much trouble actually was there? How many times have fuel oils been met which have actually been incapable of being pumped? I think Dr Wyllie has mentioned one or two tanks, and I rang him up about another one in a remote island a little while ago, where oil had been in storage since, I think, 1949. But how much real trouble has there actually been?

Captain L. E. S. H. Le Bailly: I cannot recall how much of our oil is stored above ground, and how much is below, but I think I am right in saying that in the winter of 1947, which was a very, very cold one, very little of the above-ground oil was usable. At one time in Invergordon somebody dropped a 56-lb weight into the top of the oil and there it stayed.

But that was the sort of situation after the war, where a great deal of the above-ground storage had no heating. When we introduced oil into the Navy, Lord Fisher insisted that heating should be fitted in our storages, but the first world war came; it was just going to be fitted after that war, and the economy drive came and it was not fitted; it was all planned again to be fitted in 1939, and the war came again. And we had no heating in our above-ground tanks at all, and very little heating in ships' tanks, and this was really the situation which caused the trouble, opened our eyes, and brought matters to a head.

Dr D. Wyllie: The specific example mentioned by Mr Cooper is, I believe, one of the higher flow point oils purchased before 1950. This is earlier than the current specifications, which embody the flow point/viscosity pumpability clause. These higher flow point oils would not meet the present flow point viscosity requirements, and likewise would not meet the proposed pumpability test based on viscosity in the Ferranti viscometer.

C. W. G. Martin (Shell International Petroleum Co. Ltd): Captain Le Bailly referred to the pioneering decision of Admiral Fisher. I think at that time the oil supplied to the Navy had a viscosity of only about 90 sec Redwood I at 100° F—say about 21 centistokes at this temperature.

Subsequently, the Admiralty, as I remember it, endeavoured to ensure that the fuel oil would be mobile, or pumpable, at the lowest temperature it was going to meet, and thus, perhaps not unnaturally, thought in terms of 32° F. And so the maximum viscosity specification which oils had to meet was 1000 sec Redwood II at 32° F. Only later was it appreciated that a specification at this temperature could only result in fuels of widely differing viscosities at working temperatures.

Another maritime nation specified its viscosity limits at 122° F, but, after various attempts, added a pour point figure of 15° F. Just why 15° F is not very clear.

Much later came the problem of international co-operation, and interchangeability of fuels. Was the important temperature 32° F, or something quite different? People such as Admiral Frank Mason realized that this was worthy of high-level investigation, and thus began the work that has gone on until the present day.

It is a far cry from the day, many years ago, when a deputy director of Naval Contracts told me that, as he was no scientist, 1000 sec at Redwood II meant nothing to him. His recommendation was to take a sample bottle of the oil overnight, put it on the windowsill outside the office, come back in the morning, turn it upside down, and if the oil moved it was all right! He probably had his tongue in his cheek a little, but we have, I think, made a lot of progress since then. To this progress Panel F has made a considerable contribution, and many of us are delighted to see it made public.

Commander H. D. Nixon: To answer Mr Cooper's question, and further to Captain Le Bailly's statement about the troubles we had, I think that ten or fifteen years ago they were not confined entirely to oil in storage. There were cases of ships in reserve, in the winter-time, required to light up and become operational, where the oil simply could not be pumped from the tanks to the boilers in order to start up the ship. One has heard also of ships refitting, which for some reason or other have had to empty their tanks, and which were unable to pump the oil through the suction pipelines. They had to use a portable pump to move the oil from the middle of the tank, and then dig the fuel out of the remainder of the tank. Those are facts, and those sort of situations did arise.

G. C. Ackroyd: Just one more light on this: in many of the depots they have all types of oil, and it is more or less left to the storeman there to decide, in the depths of winter, which oil he should issue. He knows very well he cannot issue certain oils in winter, and he gets rid of the bad ones in summer. This does not happen now, but when Panel F first took over it was common practice. So there was certainly a definite need for Panel F to do something about specifying what oil the Admiralty should buy.

Dr C. M. Cawley: Why doesn't it happen now?

G. C. Ackroyd: Because they are getting better oils.

C. V. Hill: In 1947 the position was that the oil which was then being found unsatisfactory in unheated shore installations had been used throughout the war quite satisfactorily in the Mediterranean and the Pacific. The people who were working in the Atlantic had been getting their oil from the Western Hemisphere. In 1947 they started to use Middle East oil in the North Atlantic. Then they found the difference between these and the very low pour point, wax-free oils from the Western Hemisphere, and that, I think, really precipitated the crisis.